MIZOGUCHI

A Study of Electrical Circuit Breaking Devices

Electrical Engineering

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A STUDY OF ELECTRICAL CIRCUIT BREAKING DEVICES

BY

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THESIS

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY Gundayu Mizoguchi

ENTITLED A Study of Electrical Circuit Breaking Devices

BE ACCEPTED AS FULFILLING THIS PART OF THE REQUIREMENTS FOR THE DEGREE OF Master of Science in Electrical Engineering

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Recommendation concurred in:*

Committee on Final Examination*

*Required for doctor's degree but not for master's.

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I. INTRODUCTION.

The aim of this thesis is to study transient phenomena of current and voltage which occur when an electric circuit is broken by means of a fuse, an air breaker or an oil switch, and also to compare the advantages and disadvantages of each of the circuit breaking devices mentioned above.

About thirty years ago, when electric power was first introduced for lighting, a fuse was used to protect the circuit in case of overload. It was objectionable to most consumers, because of the interruption of service. With the great increase in use of electric power in the last fifteen years, the danger from short circuit increased greatly. Today the damage done by an electric short circuit is comparable to that caused by the explosion of a heavy charge of dynamite. A perfect device to protect human lives, machines and instruments is of vital importance in electrical power circuits.

A fuse is the simplest protective device, and it was used extensively in small power circuits. This served fairly well in lighting loads where the danger of abnormal currents was small, but, when many motors and generators were connected, accidental short circuits became more and more frequent, and the use of fuses became more and more troublesome and expensive. In order to maintain current condition with the least expense and trouble, an air circuit breaker was used in direct current circuits instead of a fuse. In this

device a single contact was broken by means of a spring. The tripping mechanism was operated by an electromagnet. Although this device was more efficient than fuse, trouble was caused by burning the contacts. Then carbon contacts were connected in parallel with the main copper contacts, so that the main contacts broke first, allowing the arc to form between carbon blocks. Later the magnetic blow-out type came into use.

When alternating current generators of large capacity were introduced, the necessity to design a new type of breakers, to guard large power circuits against short circuit, became obvious. An arc produced by breaking the current in a great power circuit made the use of an air circuit breaker out of the question. Then an oil switch was devised to interrupt the alternating current circuits in the oil without producing abnormal disturbance in the entire circuit. It extinguished the arc without giving dangers to any adjacent apparatus.

II. GENERAL THEORY.

Fundamental Theory of Transient Currents.

In direct current circuits the inductance does not enter the equation of normal current, but it is a great factor in the growing and in the decaying current. When there is any change in the current in the circuit, due to change of the electromotive force, or resistance, always a transient term appears, due to increasing or decreasing of the stored energy.

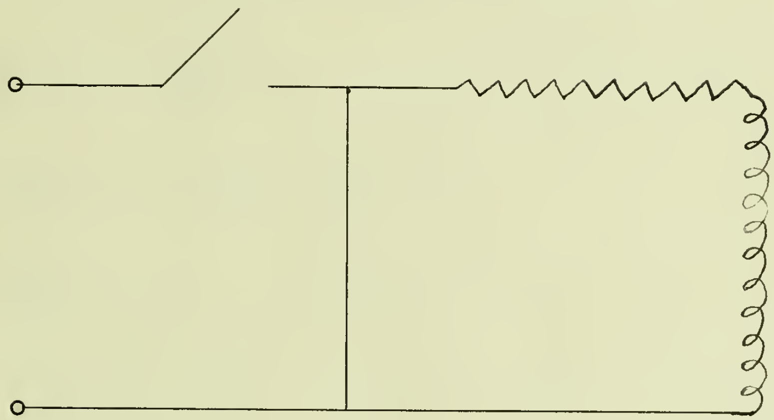


Fig. 1.

Let E be impressed voltage in volts.

I be maximum current in amperes.

r be resistance in ohms.

L be inductance in henries.

i be variable current.

t be time in seconds.

When E is impressed on the above circuit the following equation holds,

$$E = i\,r + L\frac{d\,i}{d\,t} \tag{1}$$

Now if the switch is suddenly opened and the circuit is closed with a non-resistance material at the same instant, and if we assume that there is no arc which absorbs the stored energy, equation (1) becomes,

$$0 = i\,r + L\frac{d\,i}{d\,t} \tag{2}$$

$$-\frac{r}{L}\,d\,t = \frac{d\,i}{i}$$

$$\operatorname{Log} i = -\frac{r}{L}\,t + C$$

$$\text{When } t = 0 \qquad i = I$$

$$\operatorname{Log} I = 0 + C$$

$$\operatorname{Log}\frac{i}{I} = -\frac{r}{L}\,t$$

$$i = I\,\epsilon^{-\frac{r}{L}t} \tag{3}$$

In practice, however, it is impossible to short-circuit the coil itself. Now if the coil is closed with known resistance, R, the equation (2) must be modified to the following form,

$$0 = i\,(R + r) + L\frac{d\,i}{d\,t}$$

$$i = I \epsilon^{-\frac{(R+r)}{L}t} \tag{4}$$

Where $I = \frac{E}{r}$

the extra resistance, R, helps to dissipate the stored energy more rapidly.

$E = 12$ VOLTS.
$I = 1.45$ AMP.
$r = 8.6$ OHMS.
$R = 1.68$ "
$L = .0595$ HENRIES.

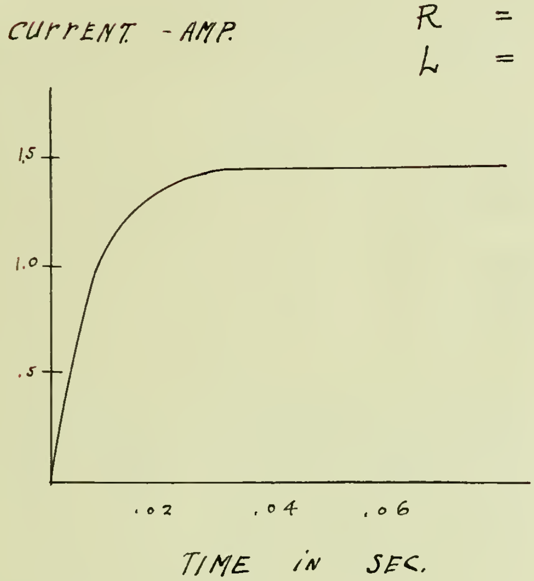


Fig. 2

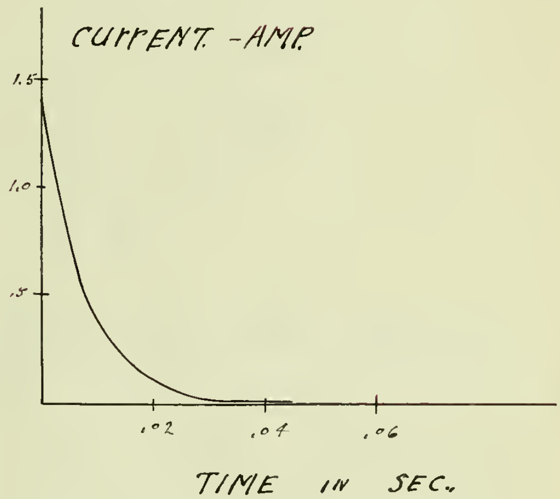


Fig. 3

In practical case, the equations (3) and (4) become useless, for the circuit is opened abruptly by the means of a circuit breaker, and the current is not allowed to flow through the circuit, until the stored energy is completely

dissipated. The energy is partly dissipated in the arc and partly transformed to the dielectric energy. The faster the speed of the opening mechanism, the smaller is the amount of the energy dissipated in the arc. If the speed were infinity great, there will be no arc between the contacts and the dielectric energy will be equal to the magnetic energy.

$$\frac{L\,I^2}{2} = \frac{C\,E^2}{2} \tag{5}$$

$$\text{or } E = I\sqrt{\frac{L}{C}} \tag{6}$$

Where I = maximum transient current

E = maximum transient voltage

L = inductance in henries

C = capacity in farads

$\frac{L}{C}$ may be called the natural impedance or surge impedance. The value of $\frac{L}{C}$ is very important. If "L" is high but "C" is low, as in the field of dynamo, even a small transient current produces very high voltage. But if "L" is low but "C" is high as in an underground cable, even large transient current produces only moderate voltage, but even moderate oscillating voltage produces large current.

Now if i r d t represents the amount of the energy dissipated in the arc, equation (5) becomes,

$$1/2\,L\,I^2 - \int_0^{t_1} i^2\,r\,d\,t = 1/2\,C\,E^2 \tag{7}$$

$$\text{or} \quad E = \frac{1}{C}\sqrt{L I^2 + 1/2 \int_0^{t_1} i^2 r \, d t} \tag{8}$$

The quantity $\int_0^{t_1} i^2 r \, d t$ can not be determined with mathematical accuracy. The current and the resistance depend upon each other and vary irregularly as shown in many oscillograms. Ionized gases formed by the arc, form a conducting path of low resistance. The conductivity depends upon the temperature, hence depends upon the "i^2 r" loss in the arc. But the current, " i ", depends upon, " r ", at the same time.

On one hand it is desirable to break the surge current as fast as possible to protect the circuit, but on the other hand, it causes development of such a high transient voltage, that it may break down the insulation.

Principle of Fuses.

Fuses are used to protect a circuit in case of overload. Generally copper or an alloy of lead and tin are used for fuses. The fuse carries the normal current but melts before the other materials in the circuits are heated to a dangerous point. When fuses are used in mines or in places where an arc is dangerous, they are enclosed in pipes or placed in a protecting box.

Fuses are expecially good for wide variation of loads, as in case of railway service, because they stand a large overload for a short time, yet they protect equipments from short circuits and extraordinary momentary peaks. Fuses are the most reliable devices for protection of apparatus

from short-circuits. Air circuit breakers or oil switches may fail to open the circuit because of mechanical defects, but abnormal current can never fail to blow up the fuses. Therefore it is desirable to connect the fuses in series with other circuit breakers for safety.

When they are placed inside of an iron box, one turn of conductor is wound under the arc gap to distort the arc. One turn of wire serves just as effectively on a small current as on a large current. The larger the current the greater is the magnetic strength of the coil. The iron cover of the fuse assists to concentrate the field at the arc gap.

Fuses are ordinarily rated at one-half current that will blow them in thirty seconds: that is 50 ampere fuses will be blown if 100 amperes flow for 30 seconds through them.

Principle of Air Circuit Breakers.

Air circuit breakers may be divided roughly into the following clases,

a. overload trip

b. underload and reverse current trip

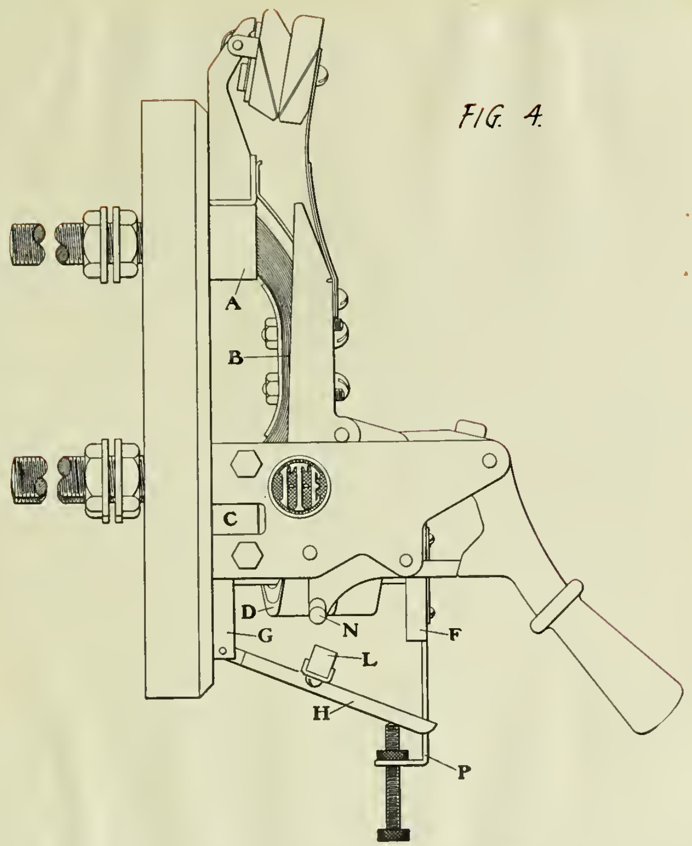
c. overvoltage trip

d. shunt trip

In this thesis investigation of the overload trip circuit breaker was especially studied.

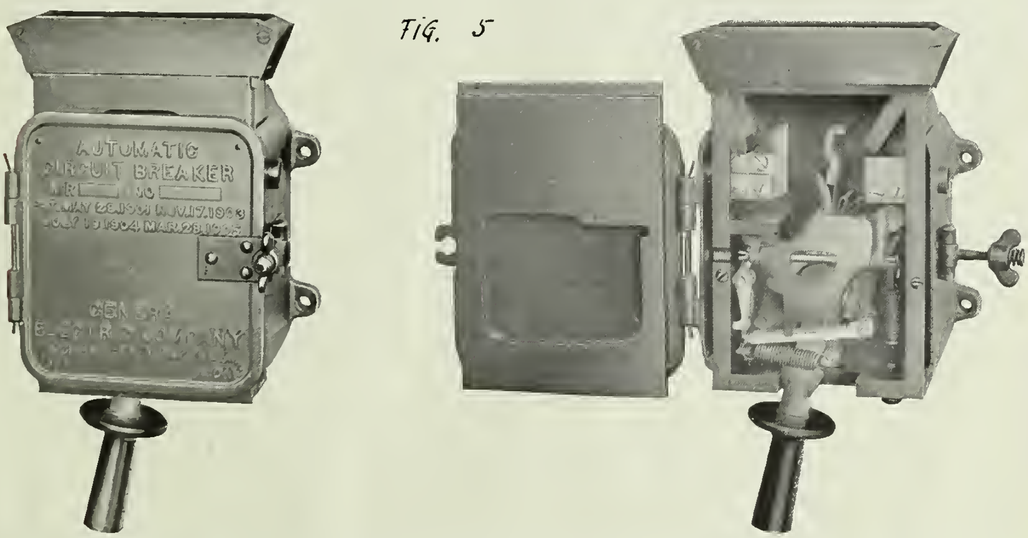
The principle of the overload circuit breaker is

FIG. 4.



CIRCUIT BREAKERS FOR RAILWAY SERVICE, TYPE MR

FIG. 5



Cover Closed

Cover Open

TYPE MR CIRCUIT BREAKER

simple, as can be seen in Fig. 4. The current enters at"A" passes through "B" and "D" and leaves at "C". The current in the coil "D" magnetizes the iron core "F" and this attracts the armature "H" in case of overload. The current required to attract the "H" can be adjusted by the screw "P" changing the distance. If "L" strikes the restraining latch "N", the spring of the contact members is released, and the breaker opens.

In Fig. 5 a strip of soft iron is extended from the core of the electromagnet to right under the arc gap. This sets up a strong magnetic field across the gap and extinguishes the arc quickly.

Underload and Reverse Current Trips. This device consists of electromagnet and armature of which is attached to a tripping lever through a toggle mechanism. The magnet acts against the tension of strong springs. If the voltage falls below certain value the springs pull the tripping lever and cause the movable parts to open the circuit.

Overvoltage Trip. In this device a plunger is placed in a solenoid, which is energized by a shunt current. Rise of the voltage above the normal value causes the breaker to open.

Both underload and overvoltage trips are used in connection with storage battery charging. The overvoltage trip is useful to cut off the current when the batteries are fully charged, while the other cuts off the current when the

batteries are discharged below a certain limit.

Shunt Trip. The shunt trip contains an electromagnet and small tripping lever. The energy may be supplied from other than the circuit, in which the breaker is connected, if it is so desired. When the shunt circuit is closed the electromagnet attracts one end of the lever, and the other end trips the circuit breaker. This device is especially desirable to operate the breaker from a distance. The current necessary to operate this device is less than one ampere. Since the shunt trip does not interfere with the automatic overload trip, one breaker is very often operated by the two methods.

Principle of Oil Circuit Breakers.

When an alternating current is broken by means of an oil switch, the arc is cooled and oil flows between the contacts when the current passes through the first zero point. If the arc is completely extinguished and is replaced by a sufficient amount of the oil, the current will not become reestablished. But if the oil distance is not large enough or if the oil is carbonized or if the power factor of the circuit is low, the current may be reestablished. In a low power factor circuit the voltage is great when the current is passing through zero, and it may be sufficient to break through the oil and reestablish the current. If the current is reestablished several times, it may lead to the destruction of the switch. Usually the dielectric strength of the oil and the speed of seperation of the contacts are the controlling factors

rather than the voltage across the arc, for it takes 50,000 volts to puncture one quarter inch of good oil. The speed of opening should be varied inversely with the frequency. A circuit breaker designed for fifteen cycles normally breaks the current at the first zero point, will continue to be reestablished until the fourth zero point.

The speed should never be so great as to break the current in less than one fourth cycle. Too rapid extinguishment of the arc causes development of high voltage which may damage the insulation of the circuit. Moreover, the extinguishment of the arc will occur near the normal zero point of current regardless of the speed. Near the zero point of current the cold oil will flow rapidly between the contacts.

In non-inductive circuits, like lighting loads, there is a little tendency to maintain the arc from sudden changes of the current. But in a highly inductive circuit, changes in the current cause high voltages, due to the term $L \frac{d\,i}{d\,t}$. This tends to maintain the arc. In a circuit of great power the energy in the arc is great. This heats the arc gas to a high temperature and makes it a good conductor by ionization. Hence it is impossible to extinguish the arc except at the zero point of the current even in non-inductive circuits.

A resistance shunt was used in oil switches at first as in air breakers but it is less effective and hard to

design and adjust it for alternating current circuits. At the present time oil switches are shunted with reactance coils. Since it takes less than one-tenth of a second from the opening of the contacts to the final rupture, a comparatively small size of wire with many turns can be used. Such a coil prevents abnormal rise of the current, due to short circuits. The main contacts may be operated at the first zero point and the final rupture takes place at the shunt contacts at the second zero point. The current passing through the shunt coil is reduced in magnitude and this makes it easier for the surrounding oil to deionize the arc gases.

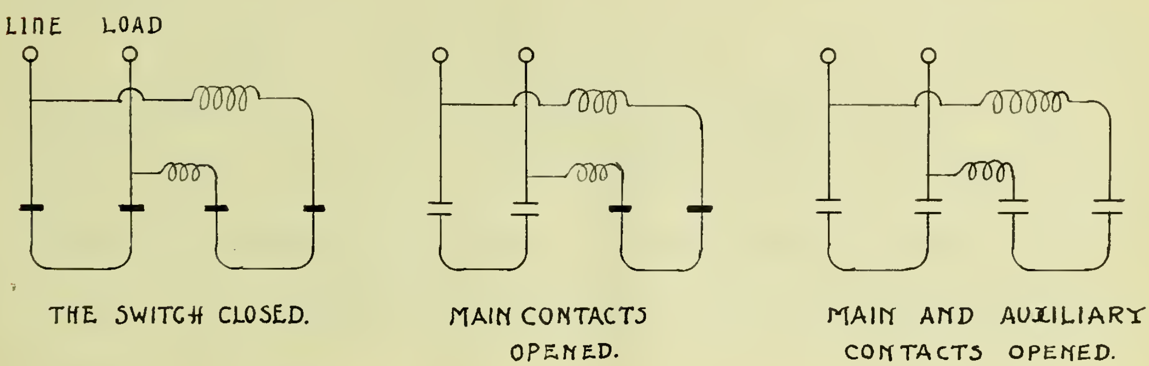


Fig. 6.

Theory of the Inverse Time Element.

In ordinary plunger circuit breakers the time between the starting of the iron core and releasing of the spring is short. This time is not affected appreciably by change of current after the starting of the core. Such an

interval in a breaker is called the "time element."

The fuse, when used as a breaking device, acts on the principle of an "inverse time element", that is, the greater the excess of current above the maximum amount, which the fuse permanently stands, the shorter is the interval before the circuit is broken. This is a desirable feature of fuses.

The inverse time element feature of a circuit breaker became more and more important for successful operation and control of electric distributing systems. The rapid increase in application of electrical power made the systems more and more complicated every year. It is especially important to maintain continuity of service, although relieving the systems from extreme currents is absolutely necessary.

Fig. 7 shows the principle of inverse time element device used in the Cutter Hammer Co., Philadelphia, Pa. The vessel, 154, contains a small quantity of especially prepared oil which surrounds the disc, 184, serving to exclude air from between their engaging faces, which are thus separated only by this oil film.

In the case of overload the pull of the armature causes gradual extension of the oil film, until, if the overload is sufficiently long continued, the film is finally ruptured and the armature, 179, moves forward without restraint, causing the circuit to be opened in the usual manner. Since additional restraint depends upon the area of the engaging surfaces, the time element can be predetermined by adjusting

the surfaces. Fig. 8 indicates the principle of another device."S" is solenoid and "P" is a plunger. The disc "D" slides up and down inside of the cylinder "C". A small hole on the

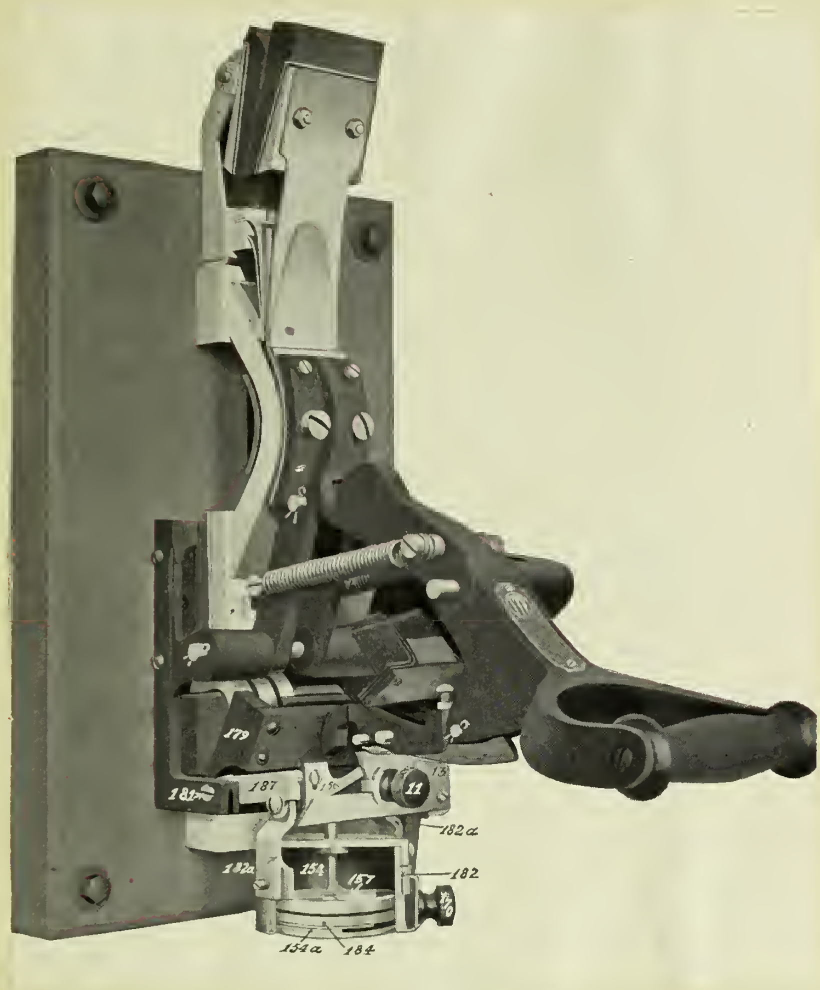


Fig. 7.

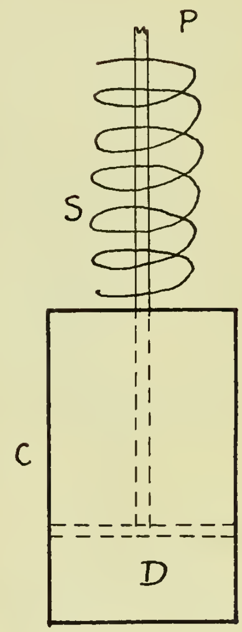


Fig. 8.

top of the cylinder allows the air to escape. If overload occurs, the plunger is pulled upward, but the pressure of the air retards the motion. The time required for the plunger to complete its travel varies inversely as the attraction of the magnet and hence inversely as the strength of the current.

III. EXPERIMENTAL DATA AND DISCUSSION OF RESULTS.

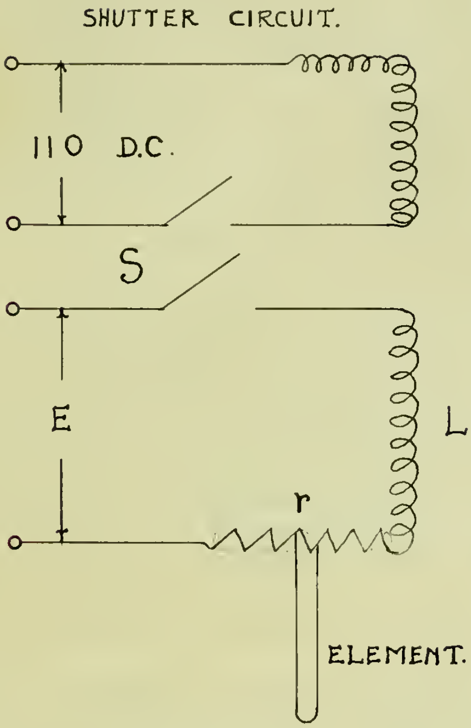


FIG 13.

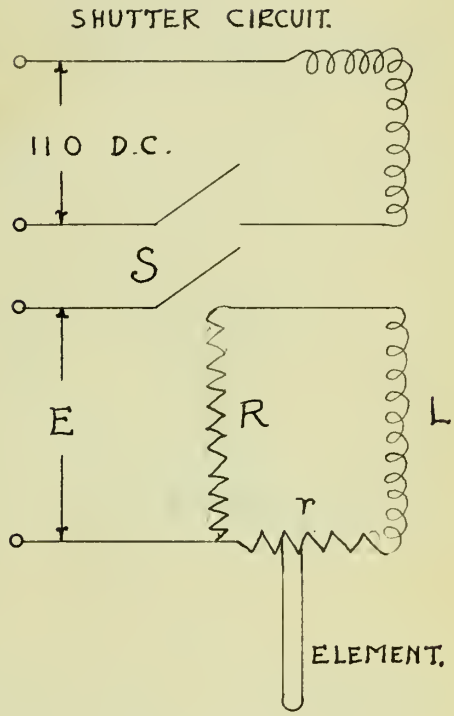


FIG 14.

<u>Growing and Decaying Currents</u>.

In the first experiment the oscillogram of growing current in a circuit, which contains resistance and inductance, was taken.

E = 12 volts from storage batteries.

I = 1.45 amperes.

r = 8.6 ohms.

L = .0595 henries.

The oscillograph used was No. 37-2, type "EM", form "C", made by the General Electric Co., Schenectady, New York. The constants of the oscillograph were as follows;

Vibrator strips, .007" x .00075" silver alloy ribbons

Resistance of vibrator, 1.2 ohms

Resistance of gold fuse, 7.0 ohms

Field current, .35 amperes

Size of the vibrator mirror, .06" x .017" x .006"

Resistance of the field, 300 ohms

Tension of vibrator strip, 4 to 6 oz.

Free vibration rate of elements, 5,000 cycles per sec.

Maximum current in the arc lamp, 12 amperes

Maximum current in the elements, 1/10 ampere

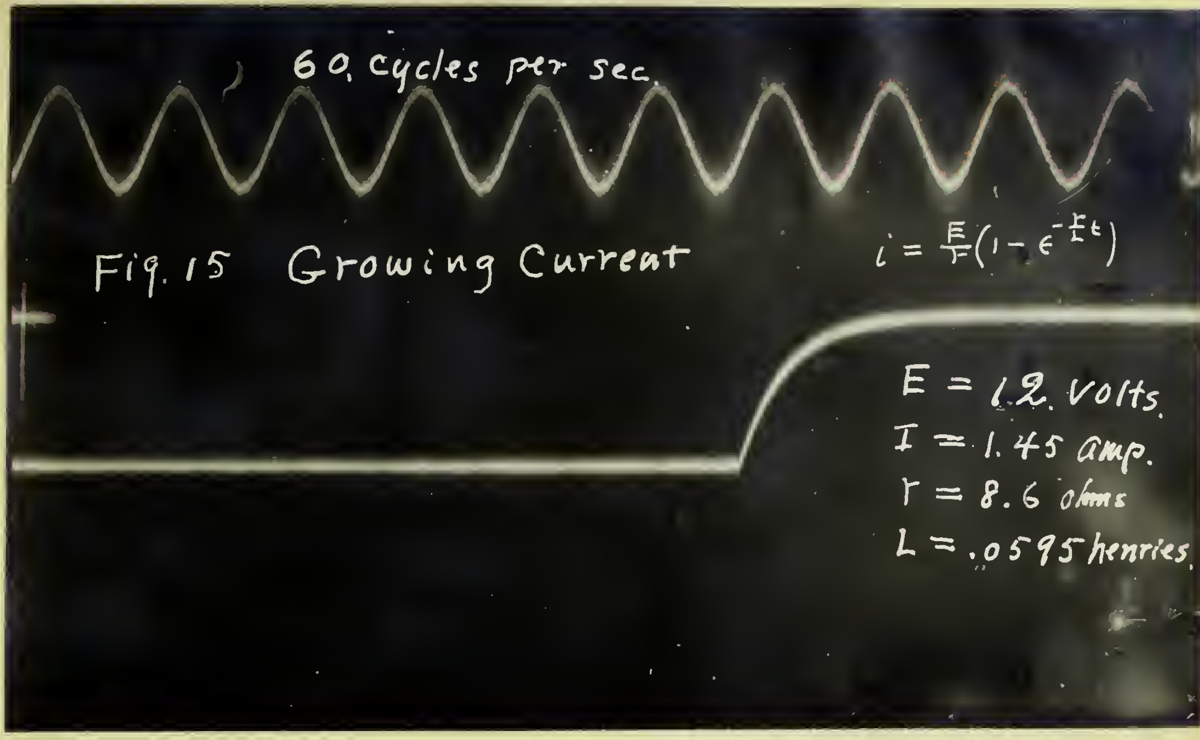
Maximum current in the synchronous motor, 2.5 amperes

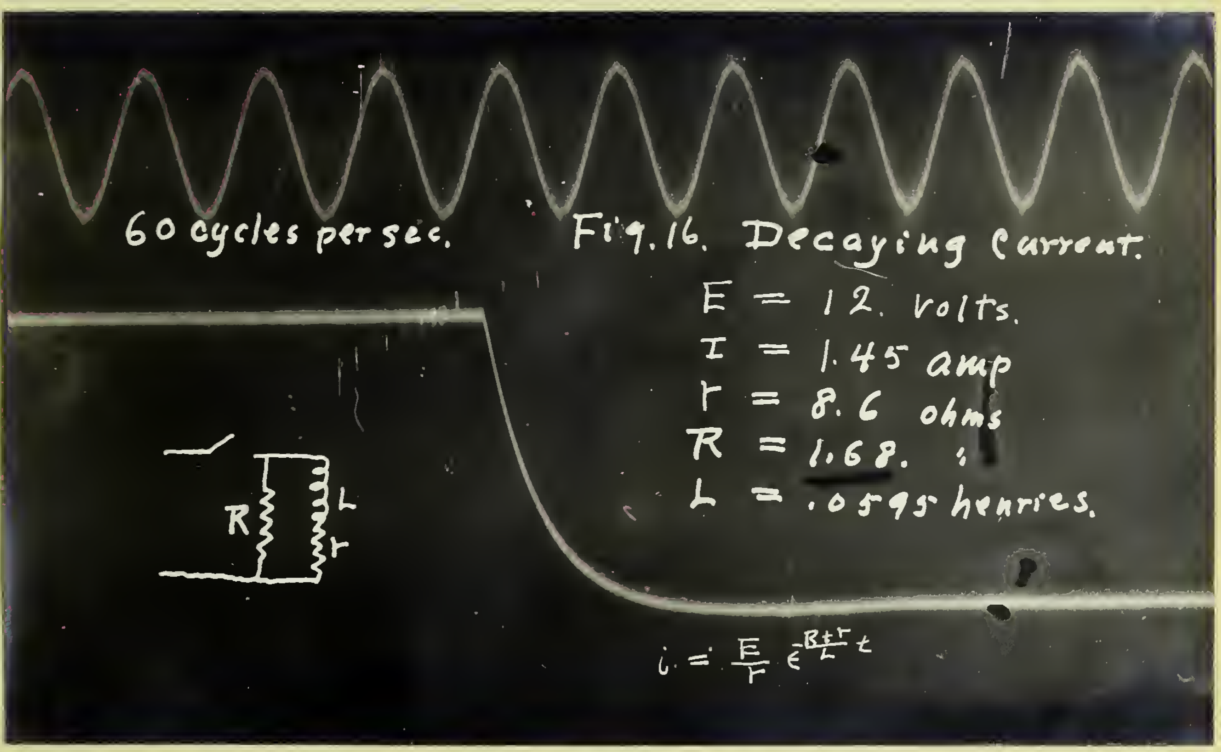
Normal current in the synchronous motor, 1.6 amperes

Maximum current in the shutter, .3 ampere

One element was connected to sixty cycles alternating current circuit to measure the time. One thousand feet of No. 6 cable and a resistance box were connected in series as the load. A double pole switch was used to close the element and shutter circuits at the same time.

In order to get the oscillogram of a decaying current the circuit was closed with a 1.68 ohm resistance, "R", as shown in Fig. 14. The switch, "S", was opened as soon as the shutter circuit was closed.


60 cycles per sec.
Fig. 15 Growing Current
$i = \frac{E}{r}(1 - \epsilon^{-\frac{r}{L}t})$
E = 12. volts.
I = 1.45 amp.
r = 8.6 ohms
L = .0595 henries.


60 cycles per sec.
Fig. 16. Decaying Current.
E = 12. volts.
I = 1.45 amp
r = 8.6 ohms
R = 1.68.
L = .0595 henries.
R
L
r
$i = \frac{E}{r}\epsilon^{\frac{R+r}{L}t}$

The two oscillograms on the preceeding page show that the curves verify the theoretical equations,

$$i = \frac{E}{r}\left(1 - \epsilon^{-\frac{r}{L}t}\right)$$

$$i = \frac{E}{r}\,\epsilon^{-\frac{r+R}{L}t}$$

Fuses.

The connections and the oscillograms are shown on the following page. A 10 ampere fuse was connected in series with 2.25 ohm resistance, "R", and switch, "S". The inductance of the circuit was negligibly small. The length of the fuse was three inches and 225 volts D.C. were impressed on the circuit by closing the switch. The arc lasted for 1 1/4 seconds as shown in curve B, Fig. 22. The switch was closed at point "A". Since there was no inductance the current built up instantly and assumed the maximum value of 100 amperes at "b". When the wire was heated the current gradually tapered down and at "C", after 0.42 seconds, the fuse started to blow and lasted 1 1/4 seconds. The interval of the arc would be partly shortened by increasing the length of the fuse.

Next, one turn of the wire was connected in series with the fuse and soft iron rods F and F' were placed at both sides of the fuse. When the switch was closed the arc went downward and burned the switch. The direction of the turn was changed, as shown in Fig. 21. Then the arc lasted only

FIG. 19.

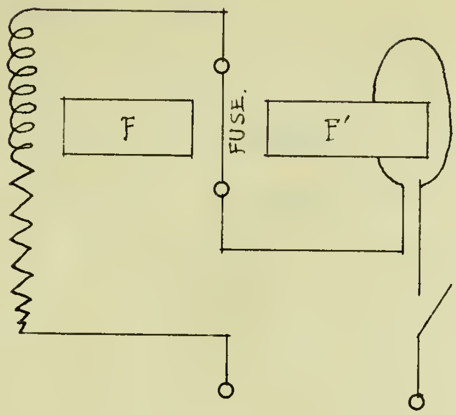
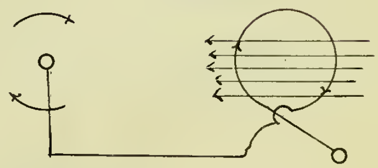


FIG. 20.

FIG. 21.



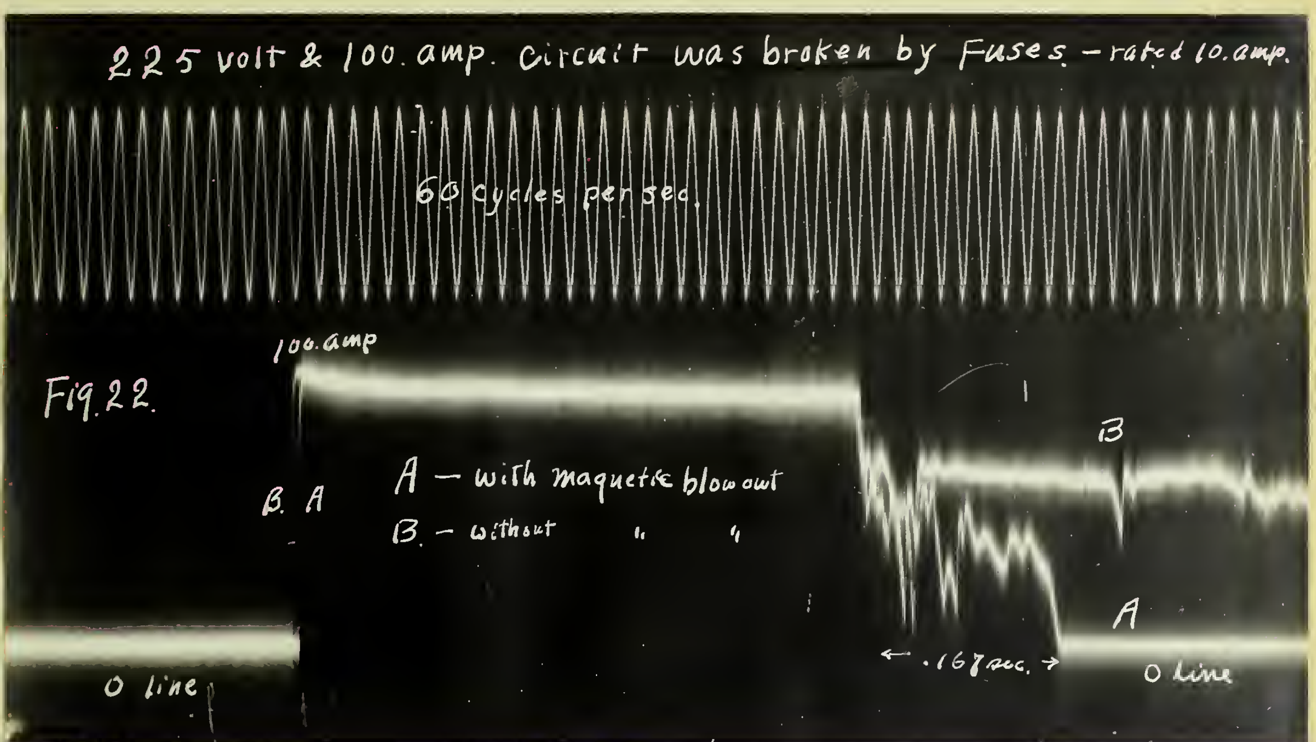


Fig. 22.

0.167 second instead of 1 1/4 seconds. This shows the marked effect of the magnetic blow-out.

Fig. 20 and Fig. 21 show the principle of magnetic blow-outs. The current is assumed to flow in the direction indicated by the arrows. The magnetic field is set up as shown by lines. In Fig. 20 magnetic lines above the fuse are helped by those of the coil, while those below the fuse oppose each other. Hence the resultant field presses the arc down. In Fig. 21 the magnetic field acts in the opposite direction and lifts the arc up, and thus extinguishes it quickly. The curves, A and B, were exposed on the same film and fortunately the switch was closed almost at the same point of the film in each case.

Experiments with a Low Voltage D.C. Generator.

In this experiment the following apparatus was used:

1 D.C.generator, 6 K.W., 6 volts, 1,000 amp., 1,100 R.P.M., No. 3,770, Ideal Electric Co.

1 automatic circuit breaker, magnetic blow-out type, 600 volts, 75 amp., type M.R. 10 D., No. 90962, General Electric Co.

1 automatic circuit breaker, type C.D., 600 volts, 100 amp., No. 188287, Westinghouse Electric Co.

1 oil switch, 600 volts, 75 amp., No. 115332, Westinghouse Electric Co.,

The connections were made as shown in the diagram. The constants of the circuit were as follows,

$$E = 6 \text{ volts}$$

$$I = 250 \text{ amp.}$$

$$R = .24 \text{ ohms}$$

$$L = .005 \text{ henries}$$

A variable resistance, R, was connected in series with 180 feet of No. 0000 cable coiled in 20 turns.

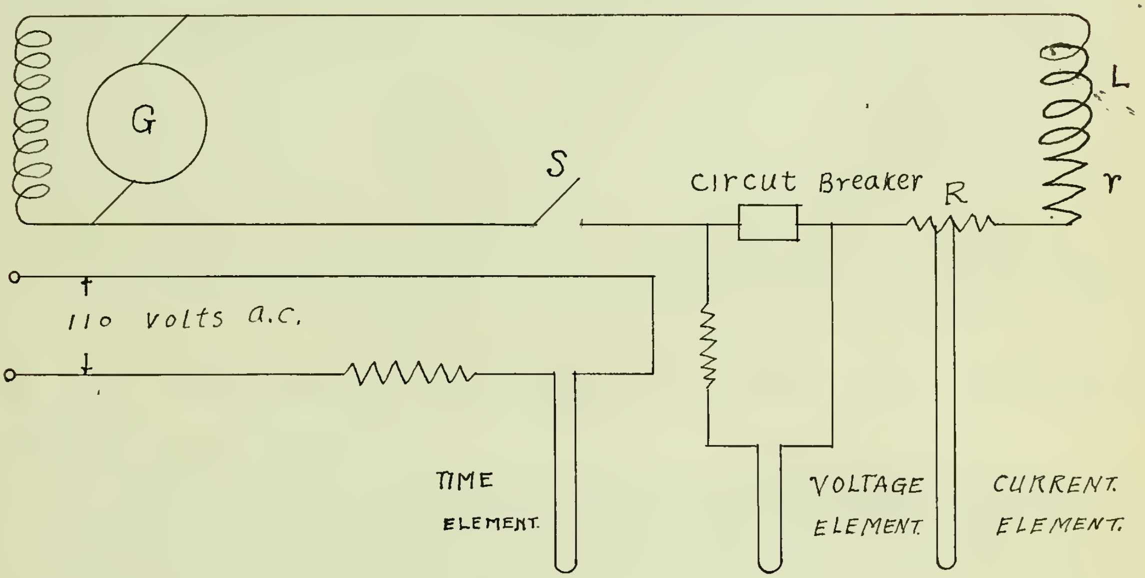


Fig. 24.

The oscillograms in Figs. 26, 27 and 28 were taken in the same circuit with the air, magnetic blow-out and oil breakers respectively. The oscillogram in Fig. 25 was taken with the air breaker and a resistance of 0.12 ohms.

Before the films were exposed the circuits were closed until the load assumed predetermined output. Then, the circuit breakers were tripped by the hands, thus opening the

circuits and obtaining the values on the oscillograms.

Owing to the very low voltage there was no visible arc when the circuit was opened. Hence, in each case the instantaneous voltage increased to three or four times the normal value. Figs. 25 and 26 show each step in the opening of the air breaker. At the point , "a", the main contacts of the breaker started to open. At "b" the carbon contacts began to open and at "c" the circuit was finally broken. The energy dissipated in the arc was negligibly small. Nearly all the stored energy was transformed into the dielectric energy. Hence,

$$E = \sqrt{\frac{L}{C}}\, I$$

In comparing the three cases the air breaker took the longest time to break, being .021 second, but on the other hand the instantaneous voltage was the lowest, due to gradual decrease of the current.

The magnetic blow-out type was the best of all, for the instantaneous voltage was nearly as low as that of the air breaker, while the time interval was only .006 second.

In respect to the time interval the oil breaker was the shortest of all. It was .004 second, but the instantaneous voltage was the highest. This was due to the sudden rupture of the current. Owing to the low voltage, the arc was small at starting, and the surrounding oil cooled it off before it had a chance to form ionized gases. Troubles, caused by breaking direct current in an oil switch, came from

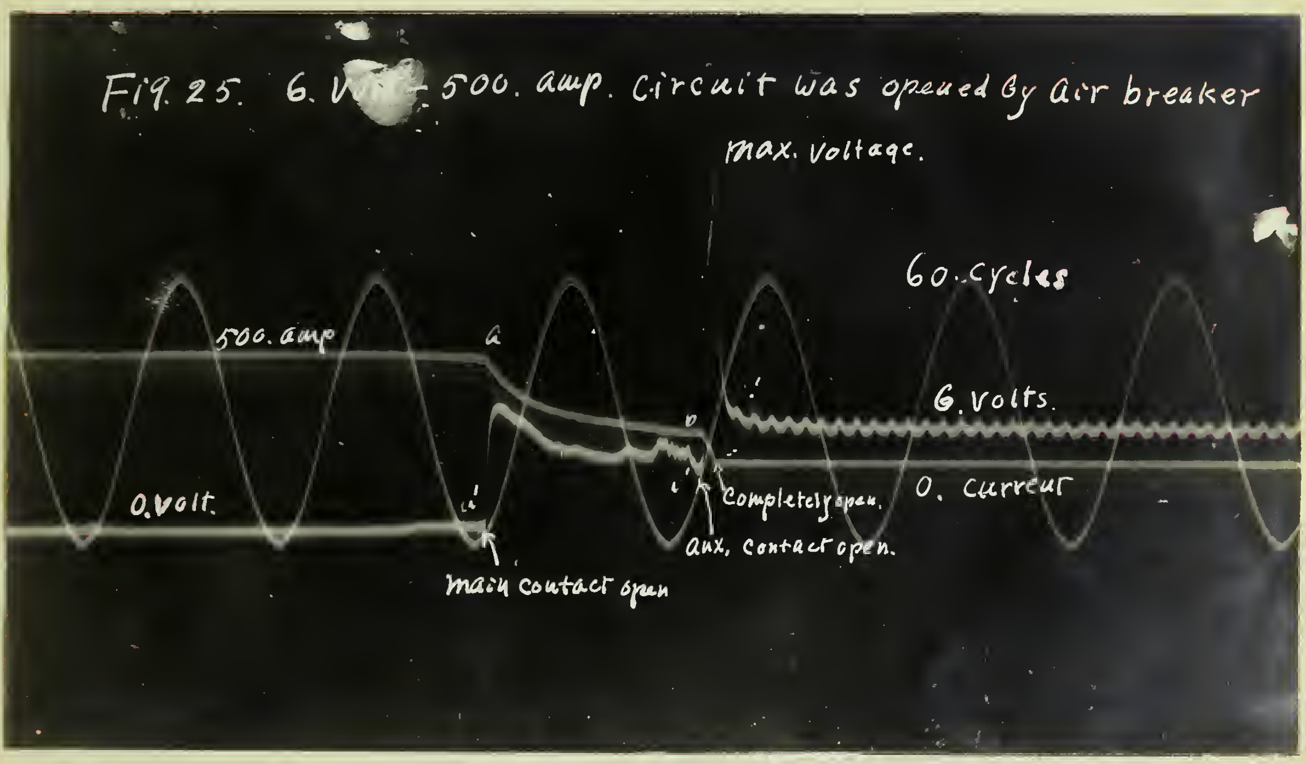


Fig. 25. 6. V[illegible] 500. amp. Circuit was opened by air breaker
max. voltage.
60. cycles
500. amp
a
6. volts.
b
0. volt.
Completely open.
0. current
aux. contact open.
main contact open

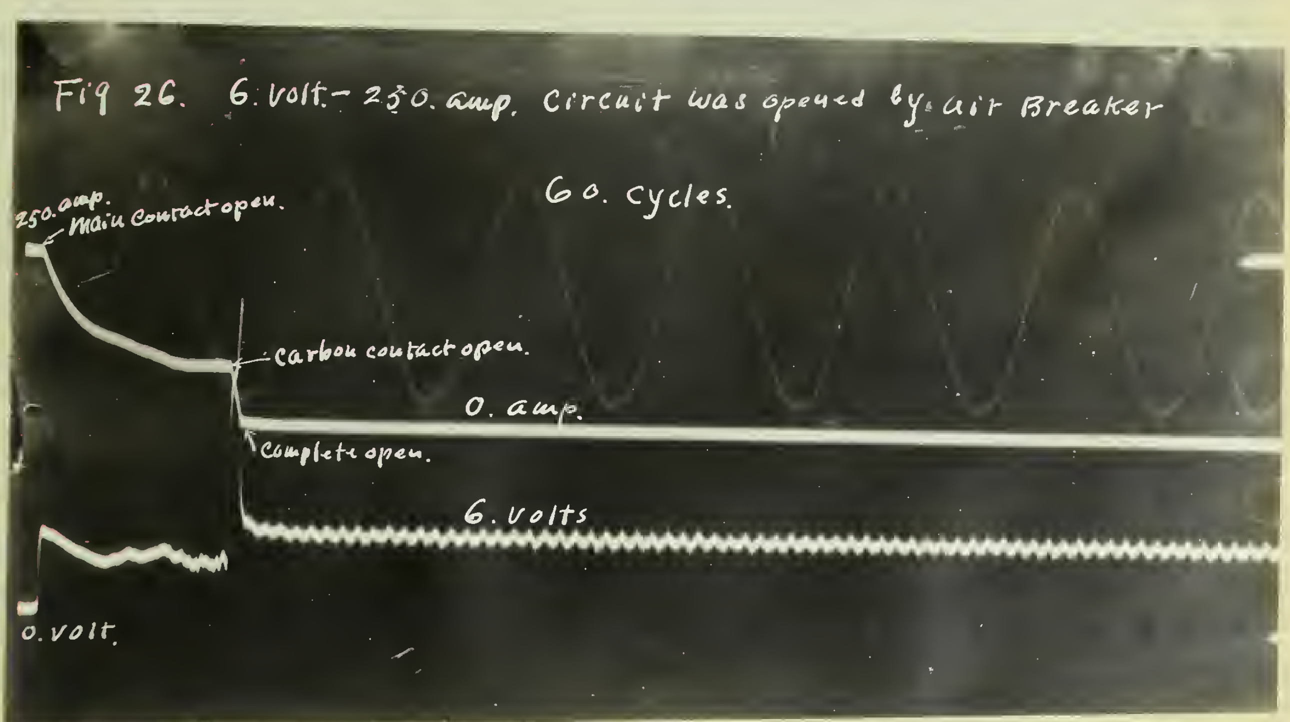


Fig 26. 6. volt - 250. amp. Circuit was opened by air Breaker
60. cycles.
250. amp.
Main contact open.
carbon contact open.
0. amp.
Complete open.
6. volts
0. volt.

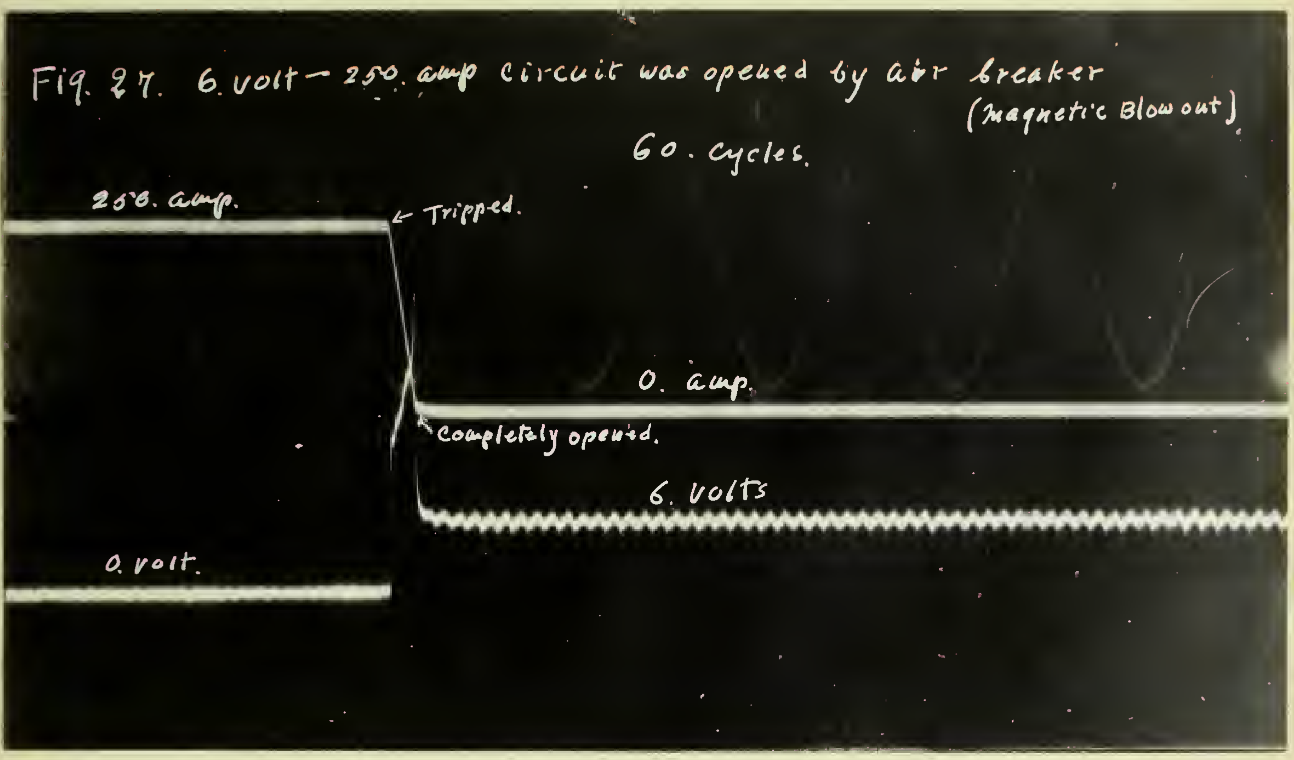


Fig. 27. 6. volt – 250. amp circuit was opened by air breaker (magnetic Blow out)
60. cycles.
250. amp.
← Tripped.
0. amp.
Completely opened.
6. volts
0. volt.

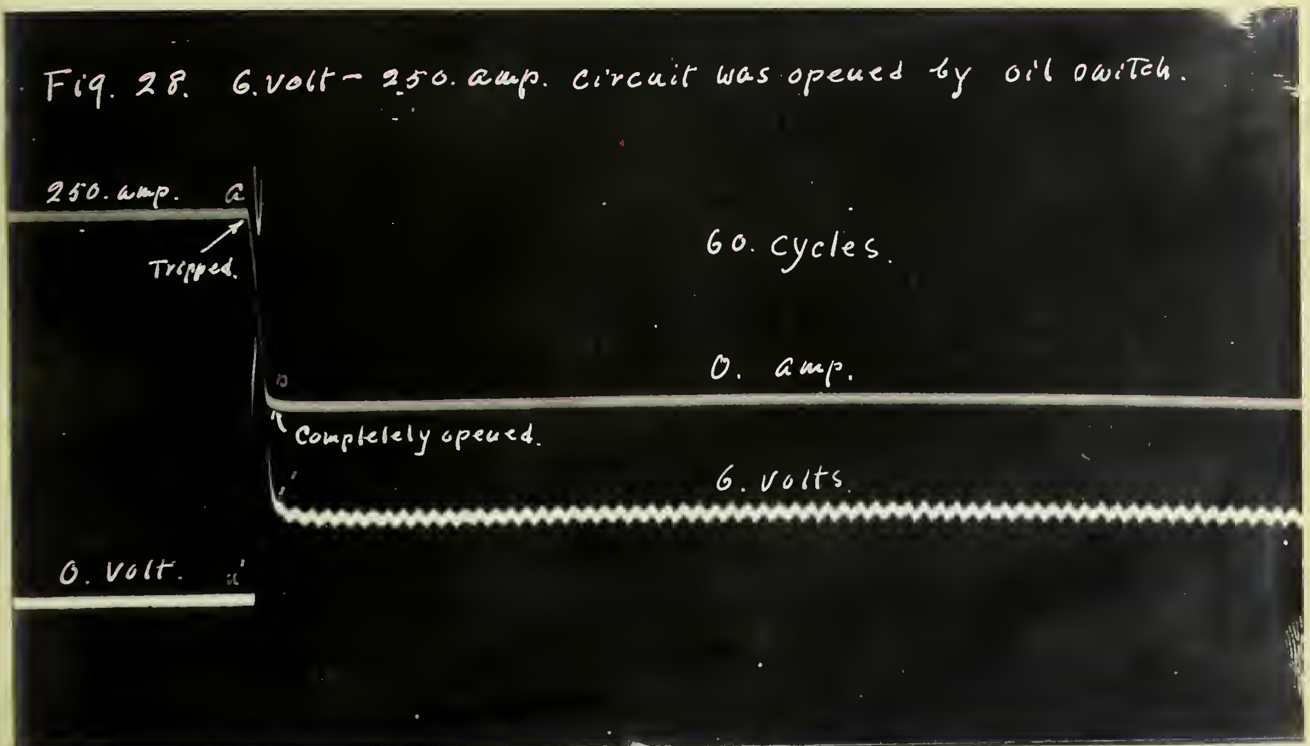


Fig. 28. 6. volt – 250. amp. circuit was opened by oil switch.
250. amp.
a
Tripped.
60. cycles.
0. amp.
b
Completely opened.
6. volts.
0. Volt.
a'

a high voltage rather than from a large current. The oil switch could break the current in a circuit of 6 volts and 1,000 amperes.more readily than in a circuit of 6 amperes and 200 volts. There was no trouble in breaking the short circuit current of the low voltage generator by the oil switch.

In all the oscillograms the voltage curves followed the zero line until the breakers were tripped at point "a", for the "I r" drops across the breaker were negligibly small. After the circuit was completely opened the voltage curves did rise to the normal voltages. The zigzag lines at no load voltages, show commutation of current. It would not be noticable if the films were driven slowly.

The alternating current wave at the top of each oscillogram was taken as a time wave. The frequency of this wave was 60 cycles per second in each case.

Experiments with 45 K.W., D.C. Generator.

The generator used was a 250 volt, 180 amp., 850 R.P.M., No. 2897 D.C. generator made by the Westinghouse Electric and Manufacturing Co., Pittsburgh, Pa. The circuit breakers and their connection were the same as in the previous case. The constants of the circuit were as follows;

E = 225 volts

I = 100 amp.

R = 2.25 ohms

L = .019 henries

The oscillograms in Figs. 29, 30 and 31 were taken in the same circuit with the air breaker, the magnetic blow-out breaker and the oil switch respectively.

Owing to the large arc between the contacts most of the stored energy was dissipated in the arc. The voltage gave only a little kick just before the final breaking point, due to abrupt rupture of the current.

The time interval was the longest in the air breaker. It took nearly .067 second. The voltage rise was only 20 per cent of the normal value. The breaking points of the main and auxiliary contacts were not indicated in the oscillograms, as in the case of the low voltage citcuit, due to large arc. Probably copper contacts were separated at point "f" after 0.017 second and the arc maintained the current during the next 0.05 second. The arc is undesirable in many respects, but it does a fine work in dissipating the stored energy, thus preventing abnormal rise of voltage. Even high transient voltage, during very short periods, may puncture the insulations.

The transient current and voltage follow almost straight lines in this case, until they approach the final rupture. The current can be represented by two straight lines, one from point "a" to "h" and the other from "h" to "b". Between points "a" and "h" the following equations can be established.

$$e = K_1 t$$

$$\text{and } i = I - K_2 t \quad \text{approximately}$$

Where K and K are some constants. If these values are substituted in the fundamental equations,

$$e = i\,r + L\,\frac{d\,i}{d\,t}$$

$$K_1\,t = (\,I - K_2 t\,)\,r + L\,\frac{d\,i}{d\,t}$$

$$\text{or } r = \frac{K_1\,t - L\,\frac{d\,i}{d\,t}}{I - K_2\,t} = \frac{K}{I - K_2\,t} \qquad (10)$$

Where K is another constant, since $L\,\frac{d\,i}{d\,t}$ is approximately constant, the same type of equation can be established between points "h" and "b".

Equation (10) indicates that the resistance in the arc varies according to the law of hyperbola, when the length of an arc is increased by uniform accelerations. The resistance is zero when the time is equal to zero. It is infinite when the maximum current "I" is equal to "K t". The resistance is roughly indicated by the following curve.

Fig. 28

The resistance of the arc is small at starting but it increases rapidly as the time of rupture approaches. The relations are complicated, for the current and the resistance depend upon each other. The equation above, however, is approximately true.

The time interval of the magnetic blow-out breaker was .017 seconds. It was about one-quarter of that of the air breaker. The distortion of arc, due to magnet, was less for shorter length arcs than for longer arcs. This is indicated clearly in Fig. 30. The slope of the current curve is small from "a" to "f", but it is almost a straight line from "f" to "b". The transient voltage was about 10 per cent higher than that of the air breaker, due to the shorter time interval.

The time interval of the oil switch was a little longer than that of the magnetic blow-out. It was about 0.025 second. In this case the conductivity of the gases, formed by the arc, was greater than in the other two cases. The current decreased slowly until it reached point "f". At this point the surrounding oil cooled the arc and broke it abruptly. This caused a sudden rise of the voltage, four times above the normal value.

Fig. 32 was also taken in the same circuit. It shows exactly the same type as Fig. 31. These prove that the oil switch operates satisfactorily in a small direct current circuit.

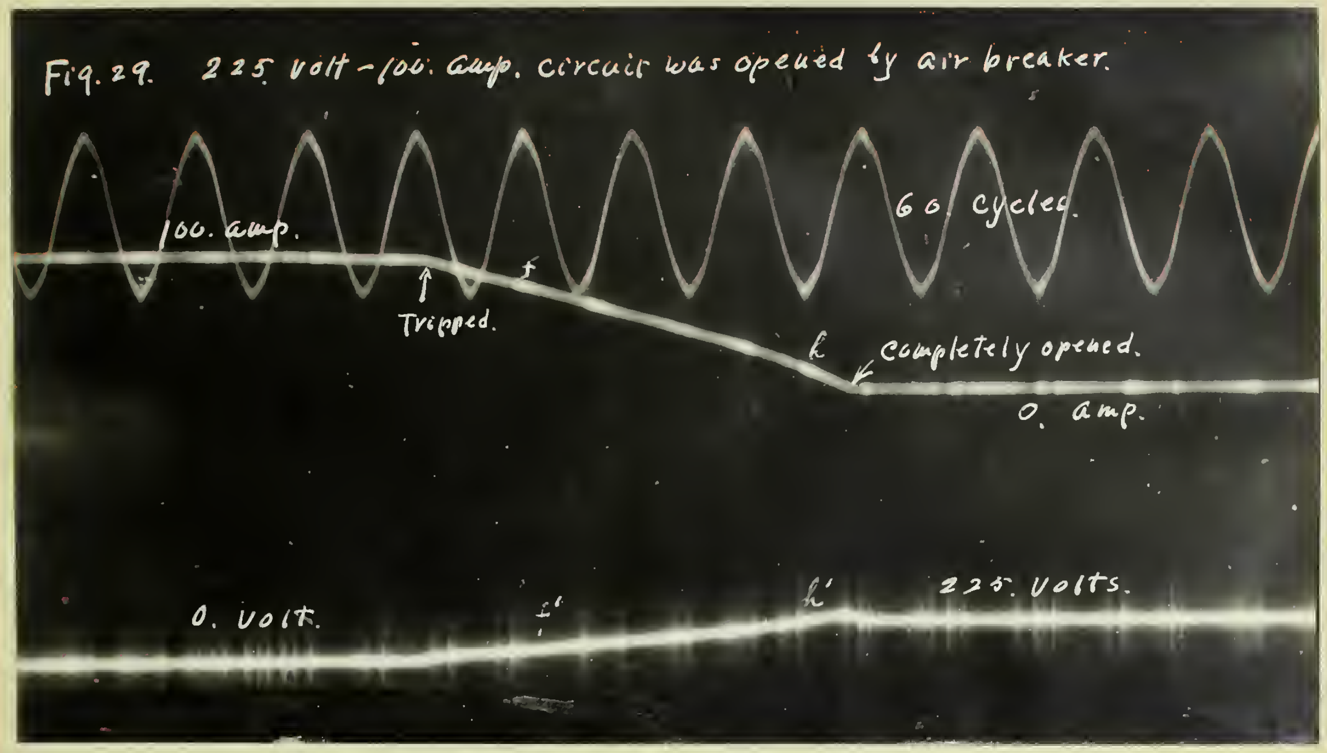


Fig. 29. 225. volt - 100. amp. circuit was opened by air breaker.
100. amp.
60. cycles.
Tripped.
f
k
completely opened.
0. amp.
0. volt.
f'
k'
225. volts.

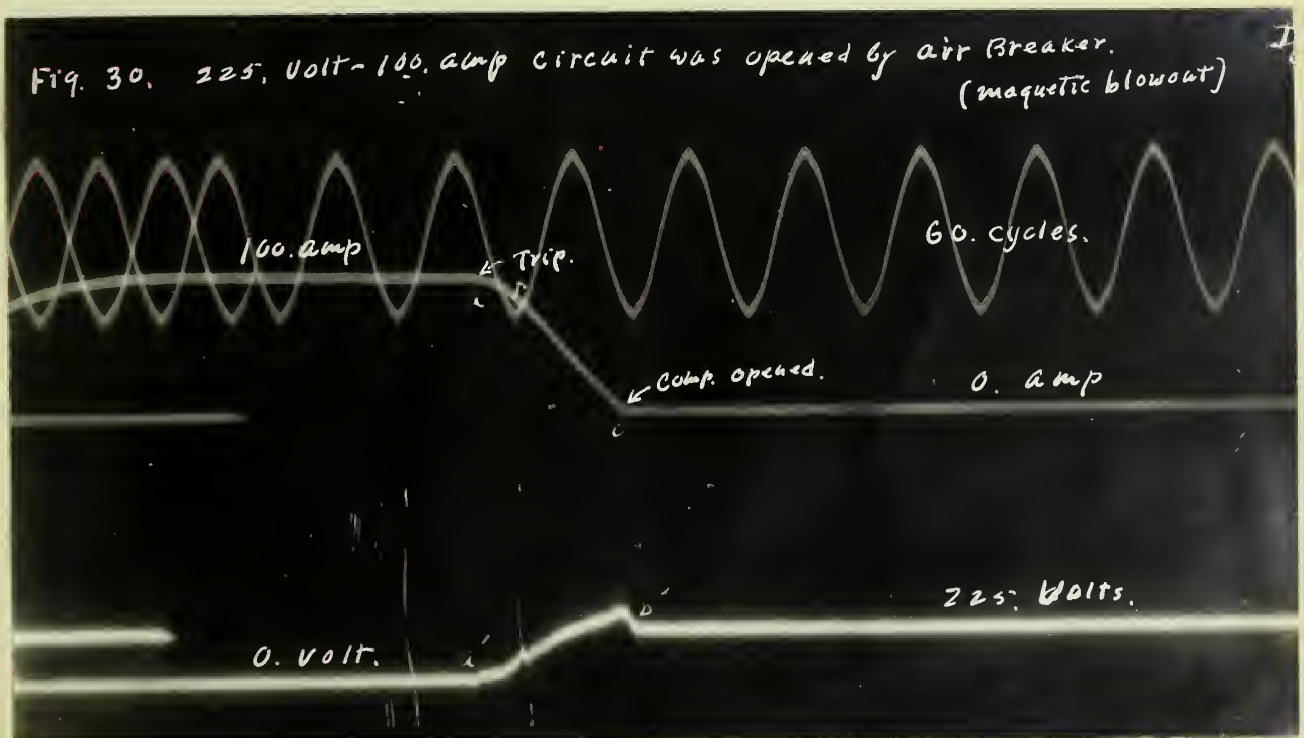


Fig. 30. 225. volt - 100. amp circuit was opened by air Breaker.
(magnetic blowout)
100. amp
Trip.
60. cycles.
Comp. opened.
0. amp
0. volt.
225. volts.

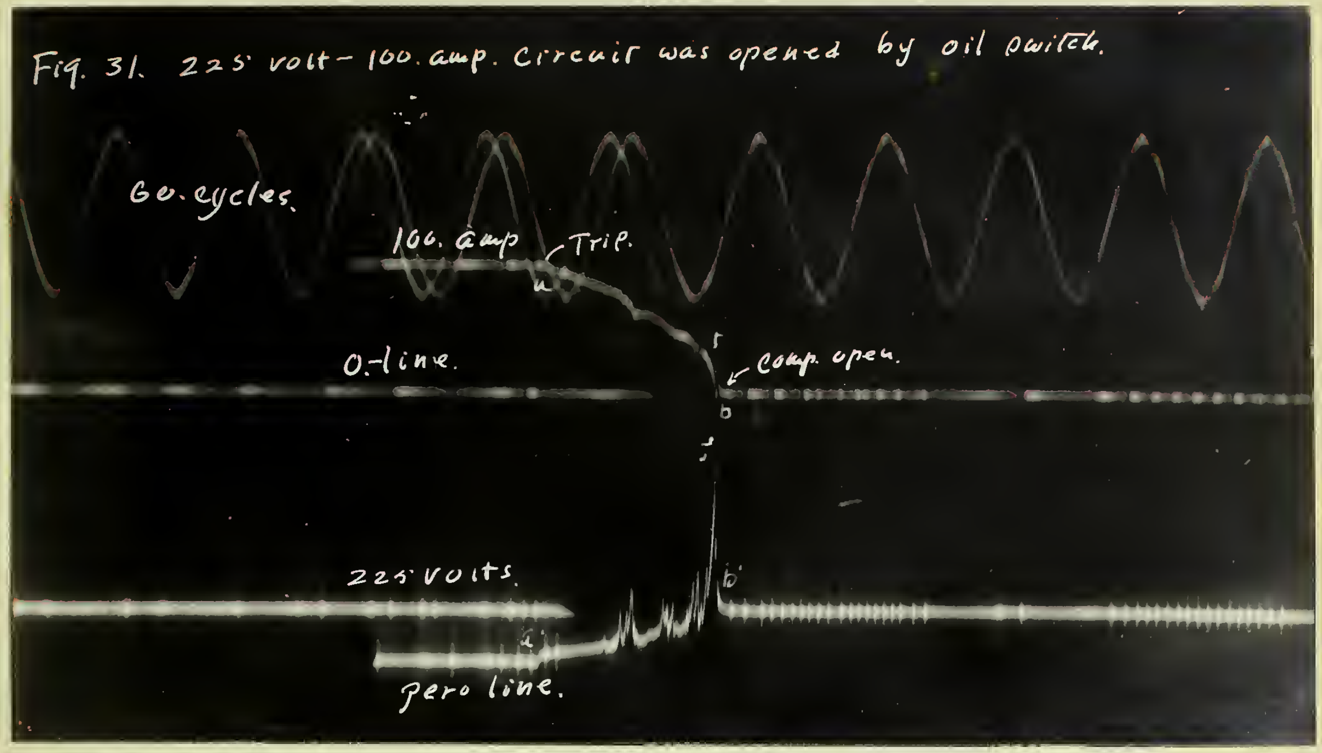


Fig. 31. 225 volt – 100. amp. circuit was opened by oil switch.

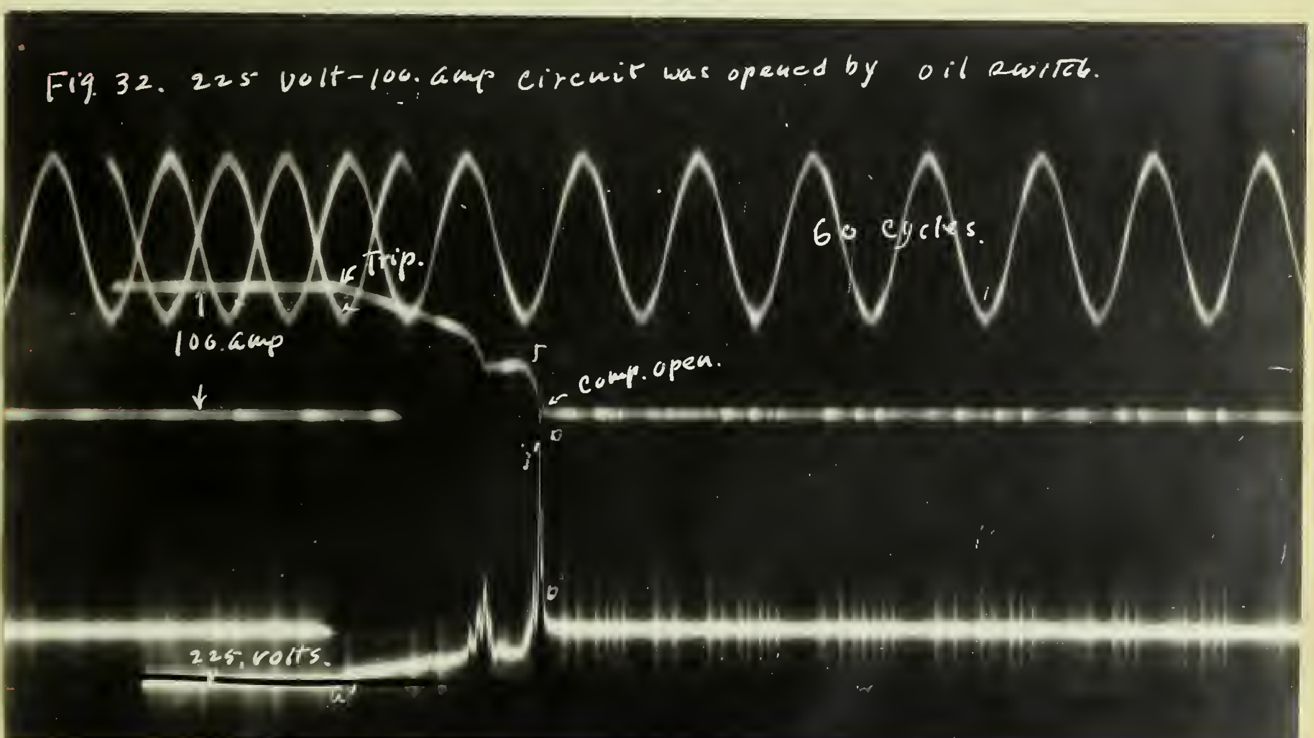


Fig. 32. 225 volt – 100. amp circuit was opened by oil switch.

[illegible]
[illegible]
[illegible]

Experiments with Alternating Current Circuits.

Fig. 34 represents the values in a highly inductive circuit. The oil switch was tripped at point "a". When the current reached the first zero point, "b", the oil cooled off the arc somewhat, and stopped the ionization of gases. The potential across the arc was, however, so great that the dielectric was punctured. This reestablished the current again. But when the current passed the second point, the distance between the contacts was greater than in the first case. The voltage was not strong enough to puncture the oil insulation at this point. If the current and the reactance were sufficiently large and if the oil were carbonized, and if the speed of opening were slow, this process of reestablishing current would continue several cycles. Sometimes it ends in the destruction of the breaker.

Fig. 35 and Fig. 36 show the voltage and exciting current of a transformer when the circuit is broken by the oil switch. In both cases the arc was extinguished at the second zero point. In inductive circuits, the breaking of the current will become harder when the frequency is increased, for reactance is proportional to the frequency. In such a circuit, the voltage is almost a maximum when the current is passing through zero, and hence the oil is more liable to puncture.

The oscillograms in Figs. 37, 38, 39, 40, 41, and 42 were taken in the same circuit with the following constants,

E = 225 volts

I = 50 amperes

r = .4 ohms

X = 4.4 ohms

f = 60 cycles per second

The connections of the apparatus and methods of the tests were the same as in the previous experiments.

Fig. 37 was taken with the air breaker. The arc lasted four cycles, which is the same period as in the direct current test. This shows that the air circuit breaker serves for an alternating current circuit as well as it does for a direct current circuit. The current decreases steadily and finally breaks at normal zero.

At first cycle the current lagged behind the voltage. This leading voltage punctured the air insluation at each zero point, and reestablished the current. This caused current to approach nearer and nearer to the same phase with the voltage, and finally the current coincided with the voltage at the last zero point.

Fig. 38 was taken with the oil switch. The oil chilled the arc when the current approached the first zero point, ionization of gases ceased, and the arc was completely extinguished. This good service was probably due to the good fresh oil, which was free from any carbon and copper particles, and large smooth contact surfaces. Good heat conductivity of the contact material, and high speed of separation also

helped to break the current. The speed of the separation is very important, but an investigation of the nature of the oil is far more important.

Figs. 39 and 41 were taken with the magnetic blow-out breaker. Figs. 40 and 42 were taken with the same breaker, without the magnetic field. It is interesting to note the time interval in each case. In Figs. 40 and 42, the current tapered down gradually, and broke off at the end of three cycles. In Figs. 39 and 41 the arc was extinguished at the first zero point. This is a remarkable feature of magnetic blow-out type. It is explained as follows: when an alternating current passes around an iron core, it magnetizes and dimagnetizes at each

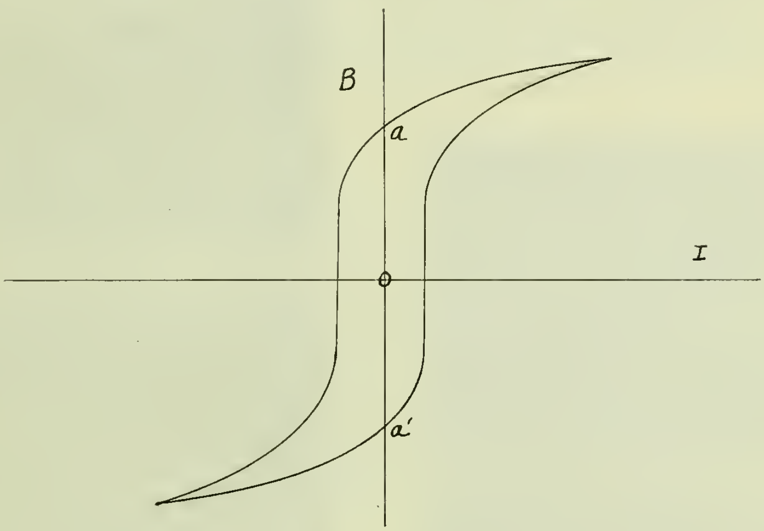


Fig. 43.

cycle. When current is passing through a zero point, residual magnetism is left in the iron core, represented by "o a" in Fig. 43. Hence the magnetic blow-out is the most effective at a normal zero point. The oscillograms show that current

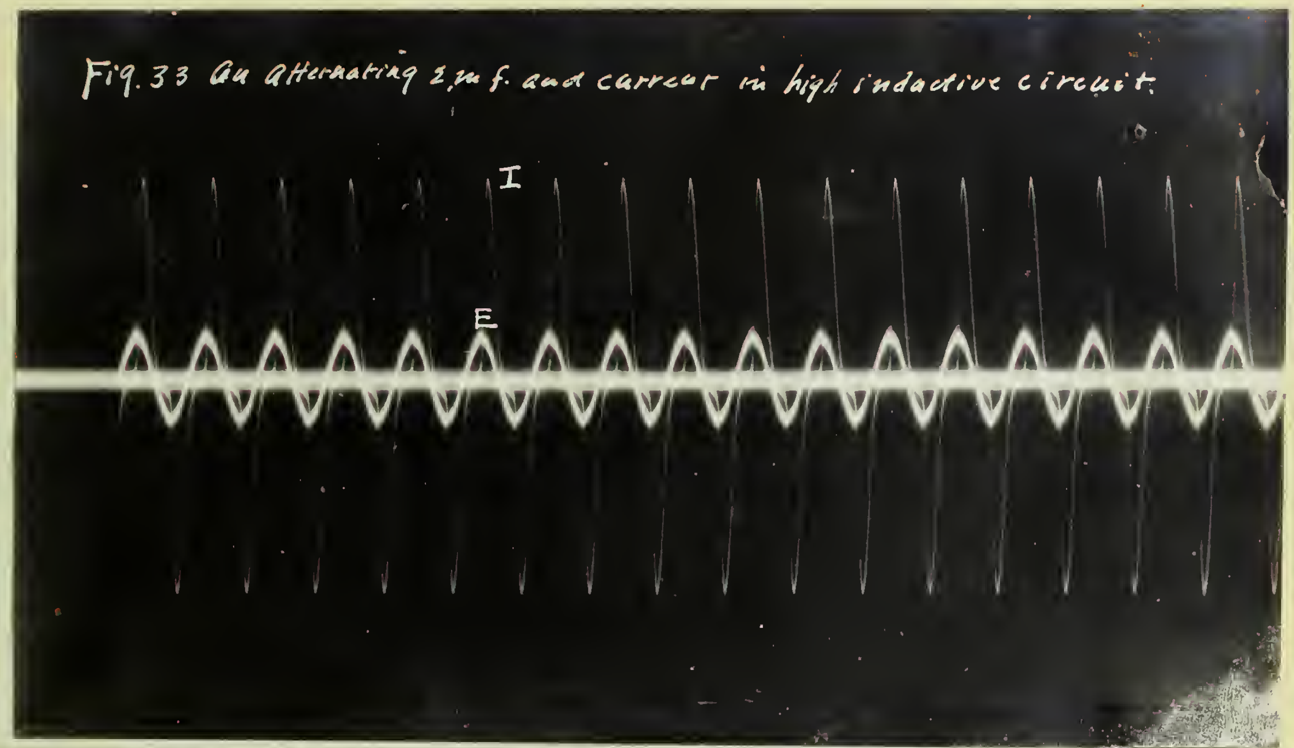


Fig. 33 An alternating e.m.f. and current in high inductive circuit.

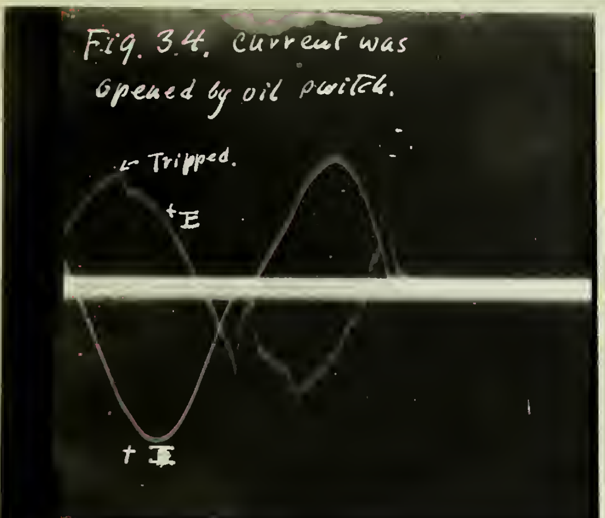
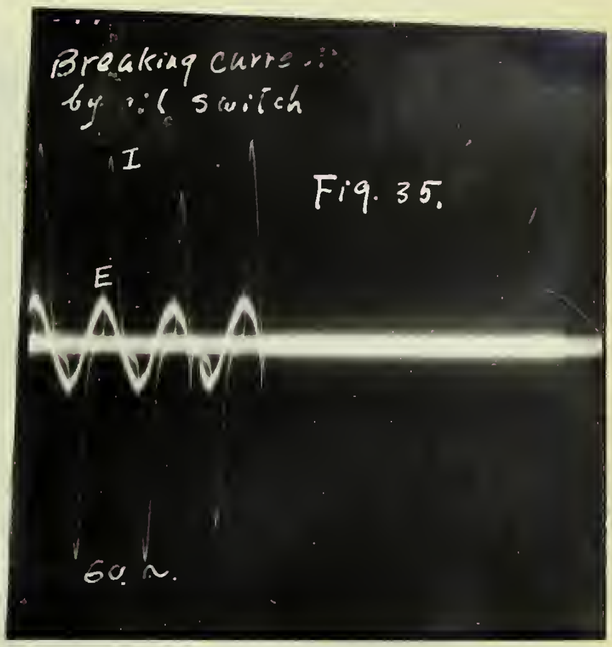


Fig. 34. Current was opened by oil switch.



Breaking curre
by oil switch

Fig. 35.

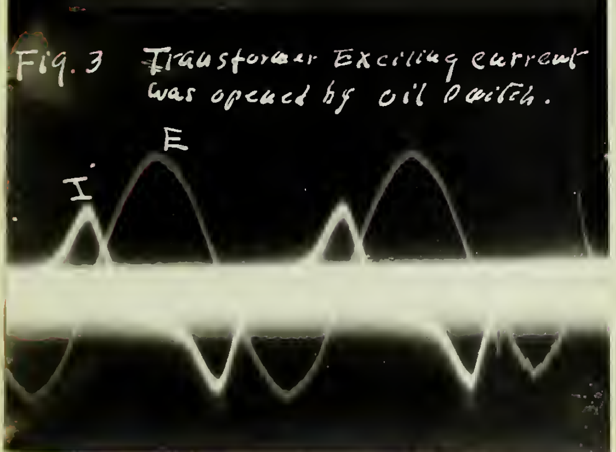


Fig. 3 Transformer Exciting current was opened by oil switch.

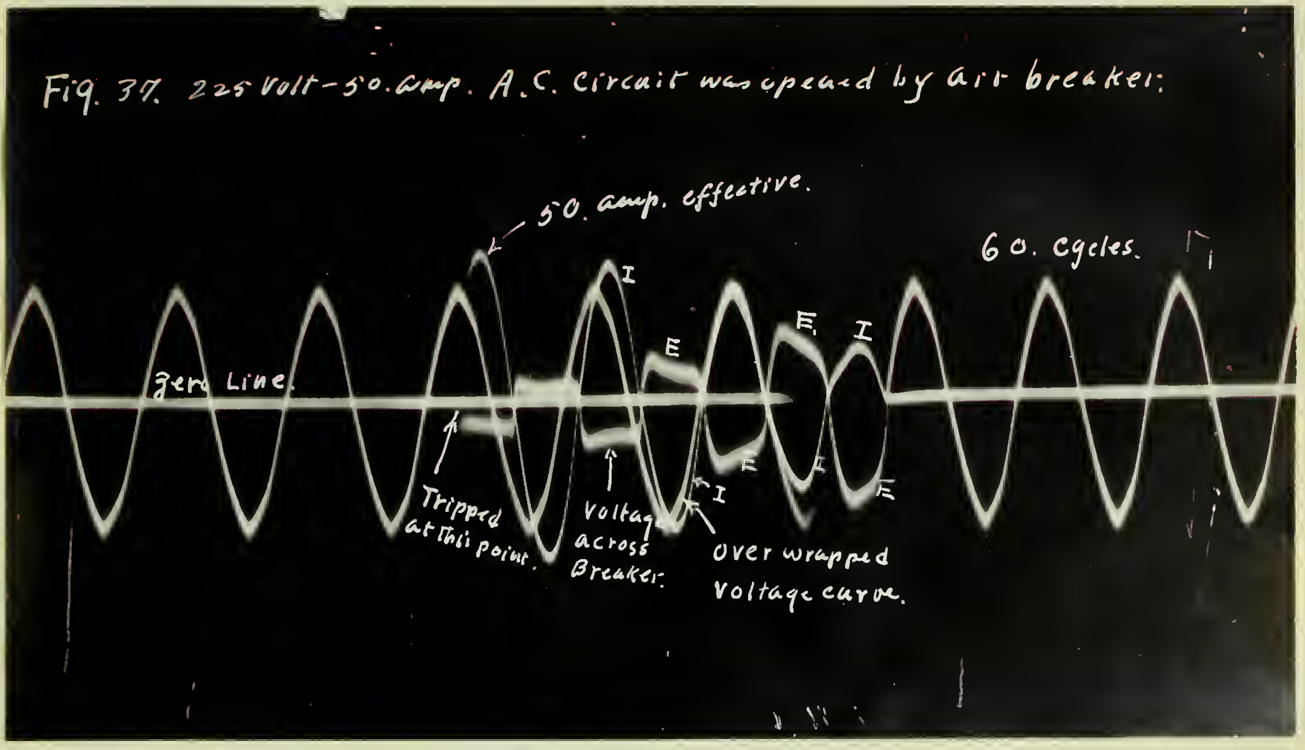


Fig. 37. 225 Volt-50. amp. A.C. circuit was opened by air breaker.
50. amp. effective.
60. cycles.
Zero Line.
I
E
E
I
E
E
I
E
Tripped at this point.
Voltage across Breaker.
over wrapped voltage curve.

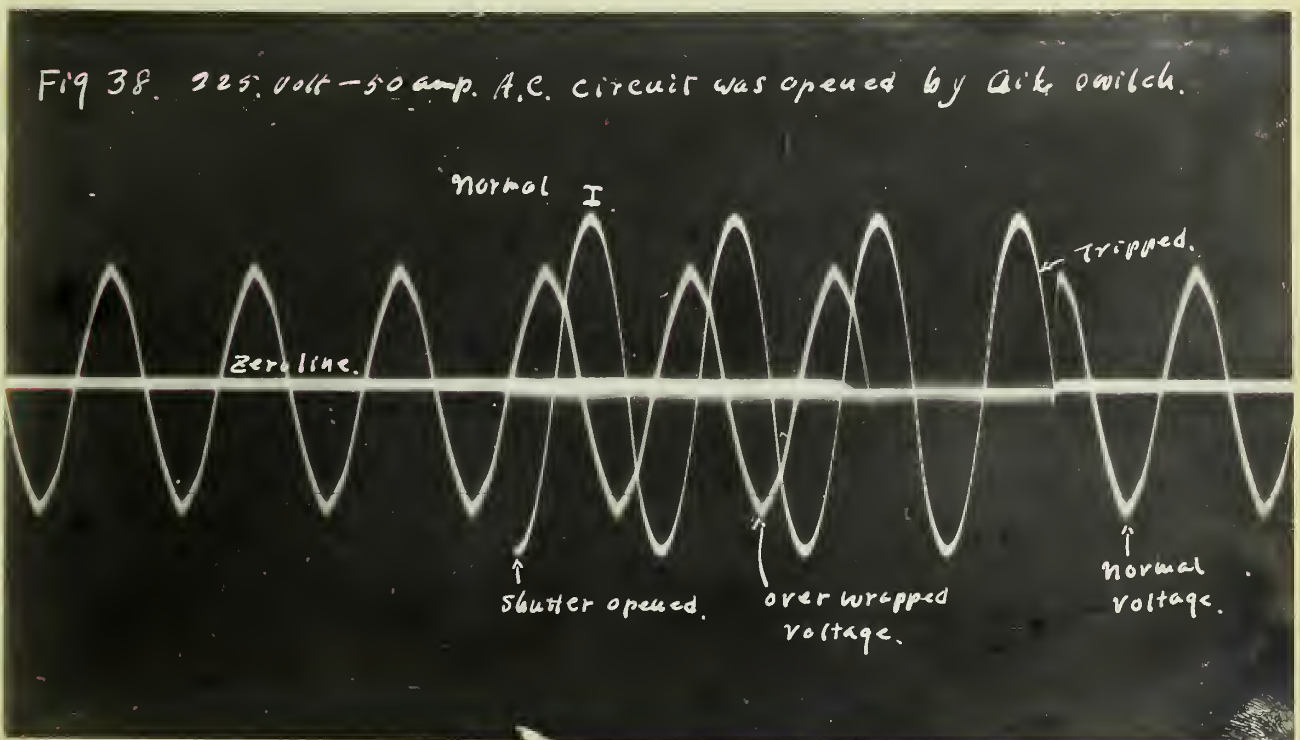


Fig 38. 225. volt-50 amp. A.C. circuit was opened by air switch.
normal
I
Tripped.
Zero line.
Shutter opened.
over wrapped voltage.
normal voltage.

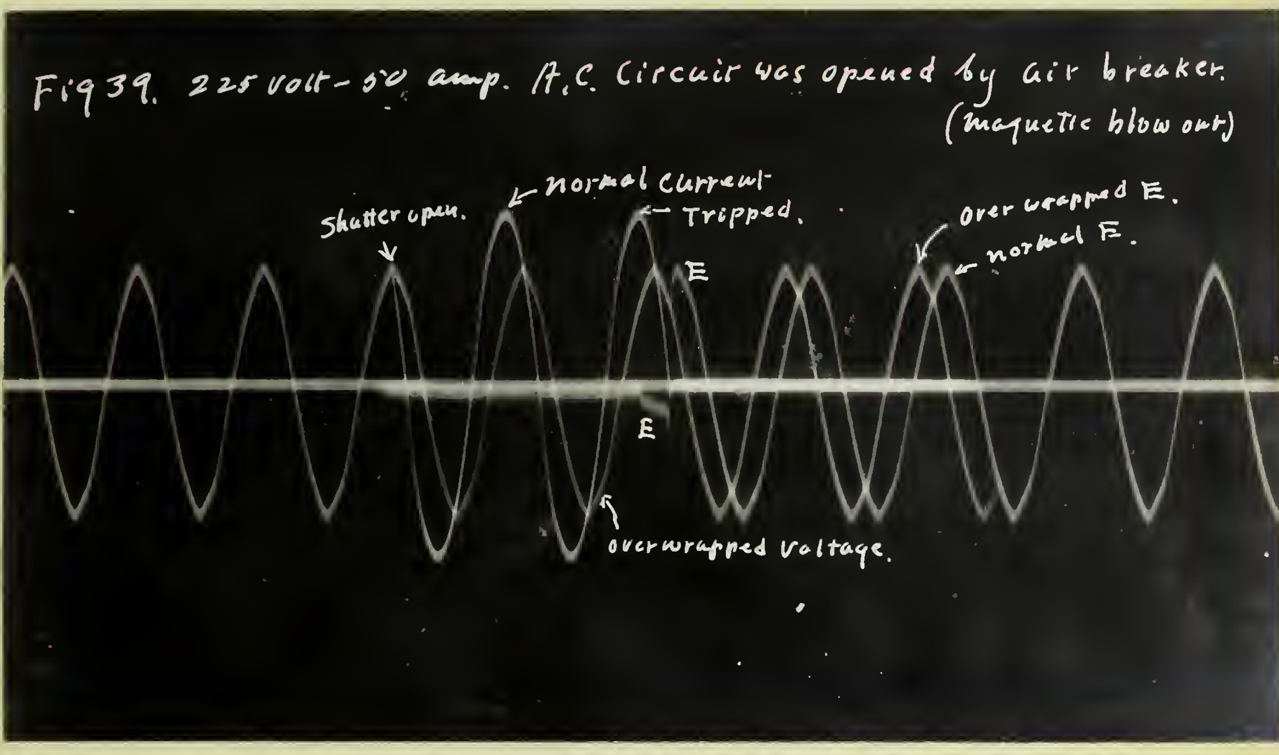


Fig 39. 225 volt - 50 amp. A.C. Circuit was opened by air breaker. (magnetic blow out)

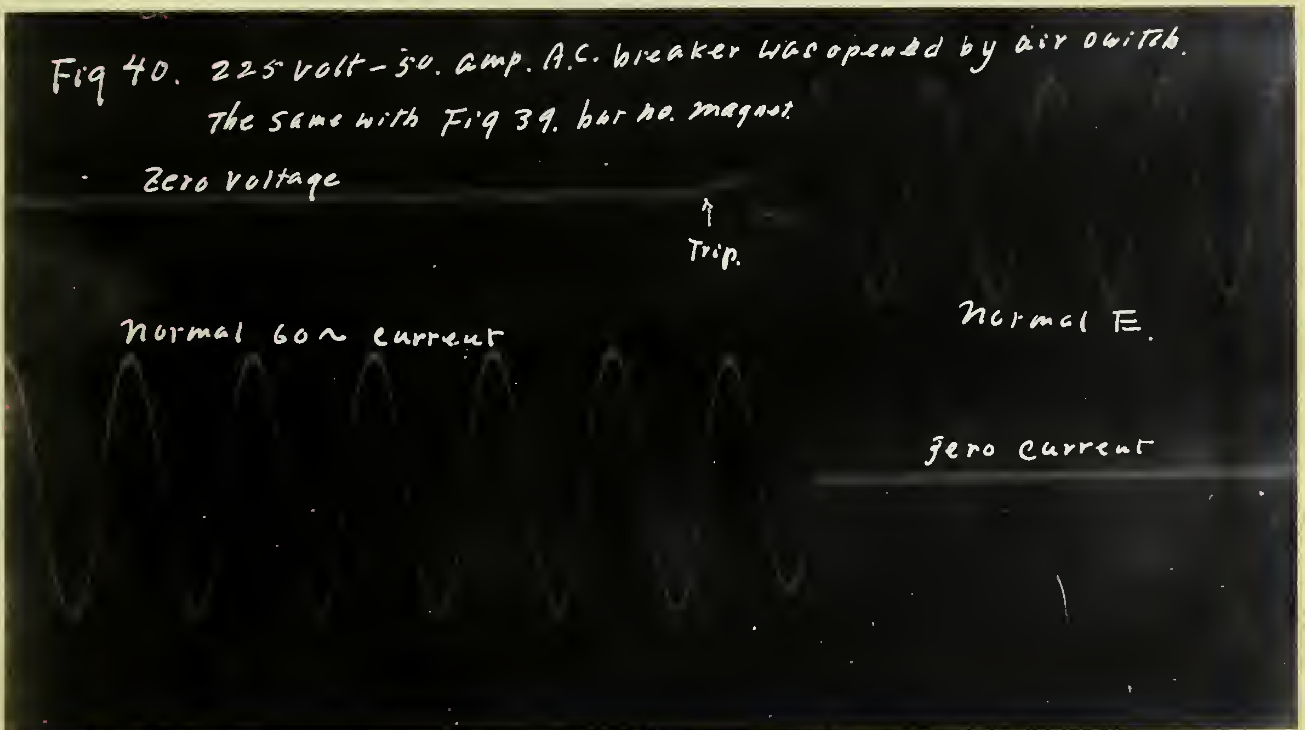


Fig 40. 225 volt - 50. amp. A.C. breaker was opened by air switch. The same with Fig 39. but no magnet.

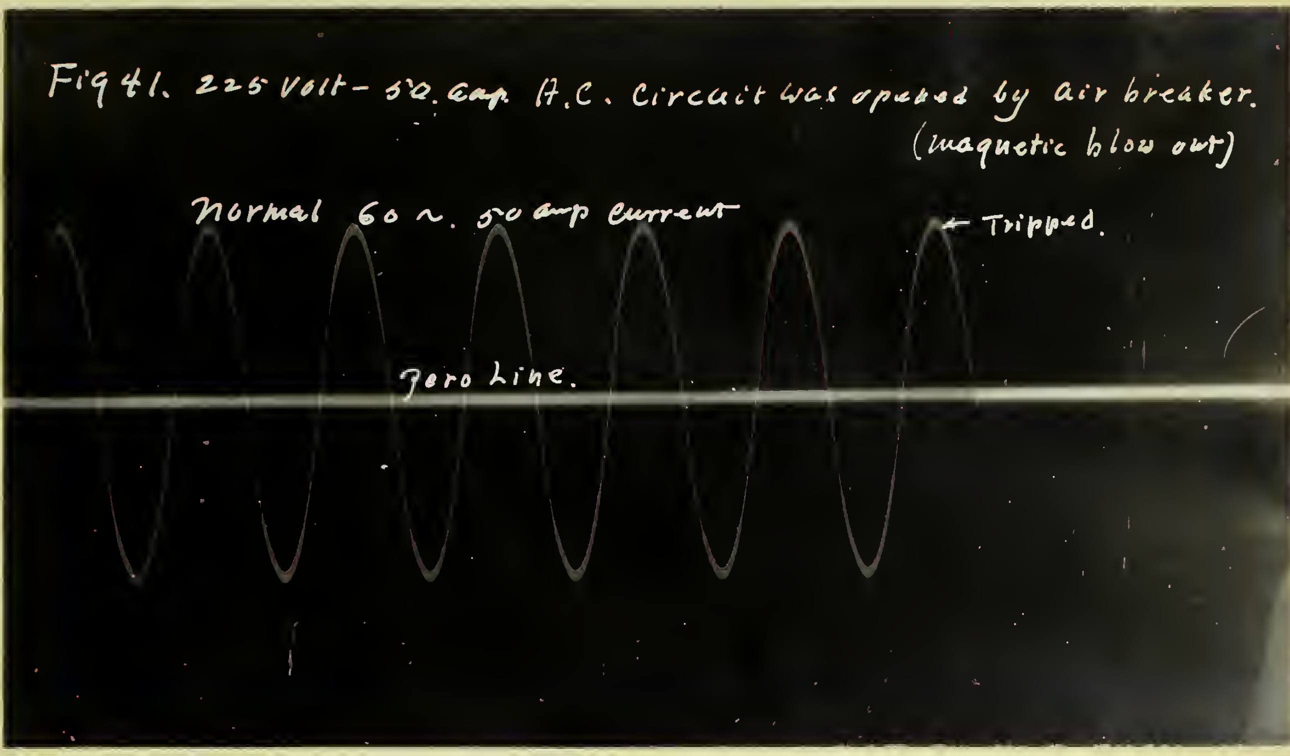


Fig 41. 225 Volt - 50 amp. A.C. Circuit was opened by air breaker.
(magnetic blow out)
Normal 60 ~. 50 amp current
← Tripped.
Zero Line.

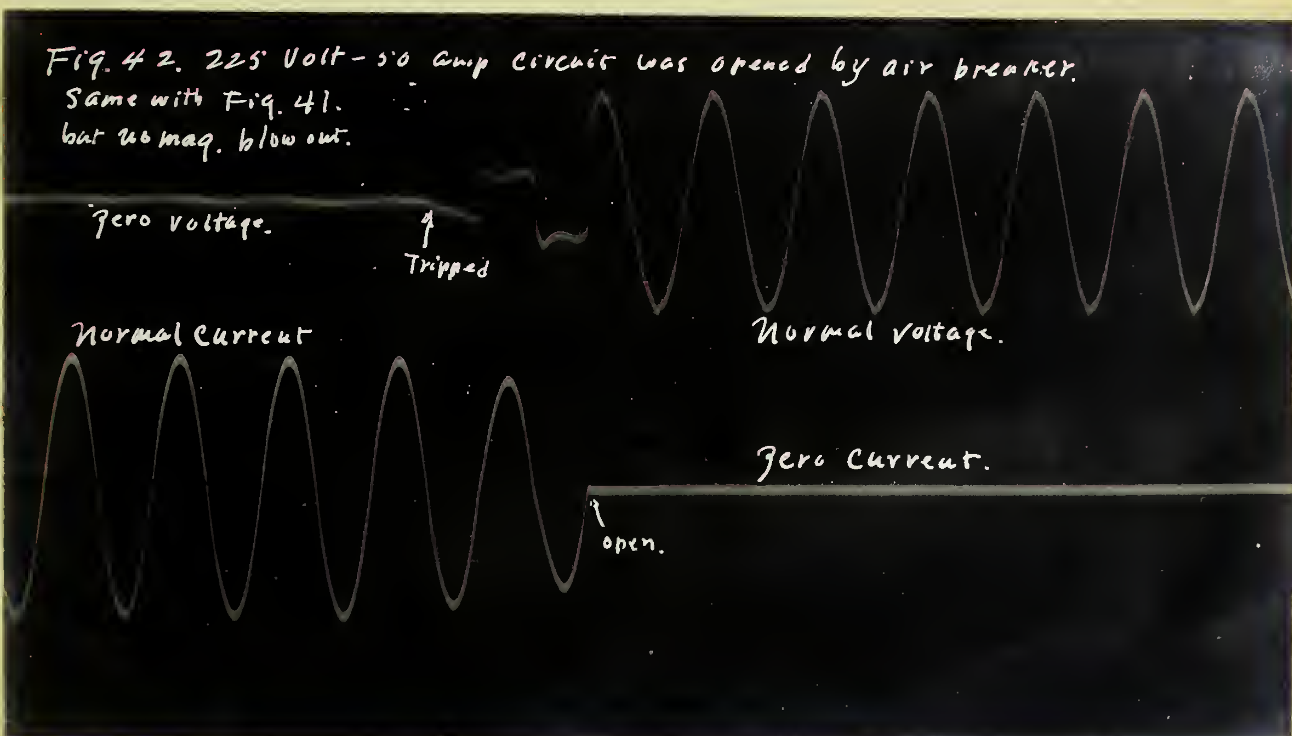


Fig. 42. 225 Volt - 50 amp circuit was opened by air breaker.
Same with Fig. 41.
but no mag. blow out.
Zero voltage.
Tripped
Normal current
Normal voltage.
Zero Current.
open.

was never broken abruptly, but always at normal zero. This type of air breaker acts exactly like an oil switch in an alternating current.

Many engineers believe that an air breaker brings greater surges and higher abnormal voltage. The oscillograms indicate this is not the case. In an air breaker, resistance is gradually increased, when the distance of separation increases and the current dies down gradually. Naturally this decreasing current prevents great rise in voltage. It is less than that of an oil switch, which breaks the current more suddenly. Moreover the cost of an air breaker is only 1/3 or 1/2 of an oil switch of the same capacity. When it is used in transmission lines, it can be exposed out of doors, and the arc gives no danger, while the oil switch needs additional expense for covering.

Short Circuit and Time Element Tests.

The time element tests were made on the low voltage generator circuit. Figs. 47 to 54 are the oscillograms taken to find the relative values of time intervals and currents, on the air breaker, on the magnetic blow-out breaker, on ordinary fuse wire and on No. 17 copper wire. Fuses of 10, 35, and 50 amperes were tested and the average values were plotted in the curve, "B", Fig. 46. The curve "A" of the same figure shows the result of the test made on No. 17 copper wire. Ordinary fuse and copper wires follow "the principle of inverse time

element", that is, the greater the current the shorter is the time required to break it. This is a desirable feature of fuses.

Figs. 55, 56, 57, and 58 show short circuit tests with the air breaker, with the magnetic blow-out breaker and with fuses. The short circuit current was obtained from the 1,000 ampere generator.

The time interval was the shortest in the magnetic blow-out breaker. It was 0.045 second. The air breaker opened in 0.061 second. A fuse of 10 amperes was blown in 0.07 second, and No. 17 copper wire was blown in 0.67 second.

Some persons believe that a circuit breaker must open in order to protect the circuit, before the short circuit current reaches its maximum value. But it is practically impossible, due to the quick rise of current. The result of a number of tests made by Mr. E. B. Merriam, show that current increases on a dead short circuit at the rate of 1,000,000 amperes per second.

Per Cent Overload	Time Intervals in Seconds	
	Air Breaker	Magnetic Blow-out
0	permanent	permanent
12		.125
40	.133	.100
90	.100	.075
150	.084	.067
210	.074	.060
1,400	.061	.045

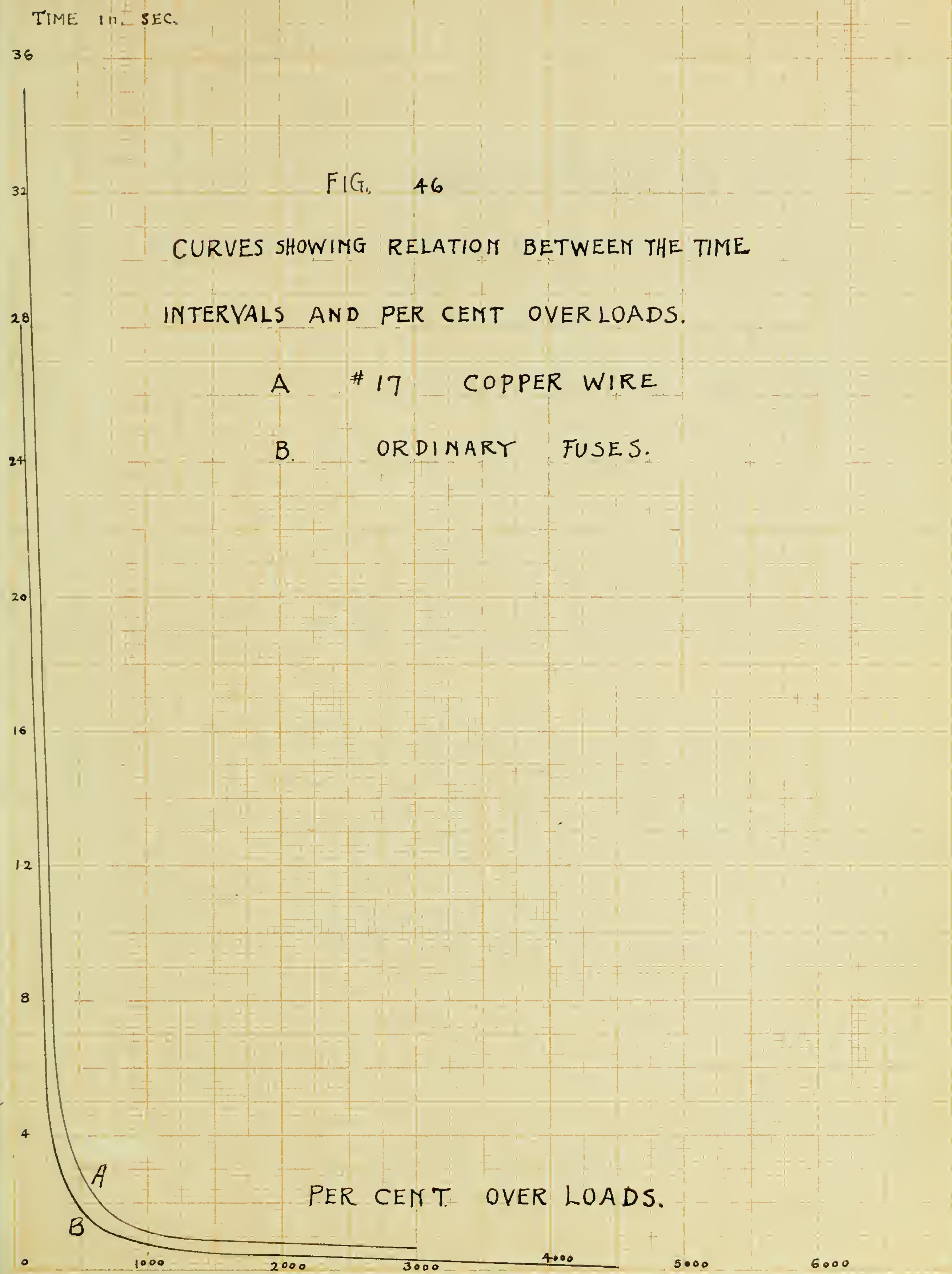


FIG. 46

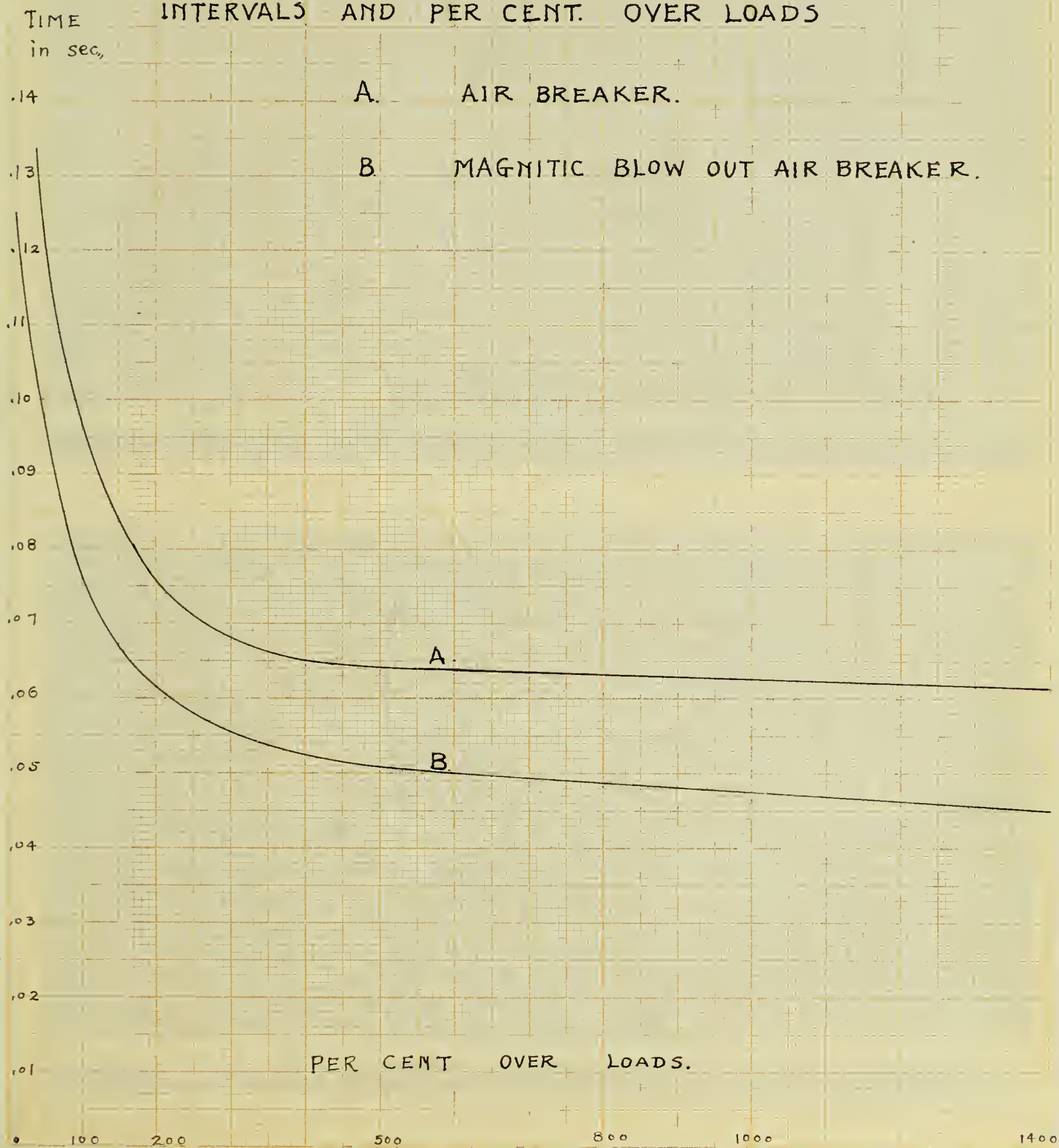
CURVES SHOWING RELATION BETWEEN THE TIME INTERVALS AND PER CENT OVERLOADS.

A #17 COPPER WIRE

B. ORDINARY FUSES.

FIG. 47.

CURVES SHOWING RELATION BETWEEN THE TIME INTERVALS AND PER CENT. OVER LOADS



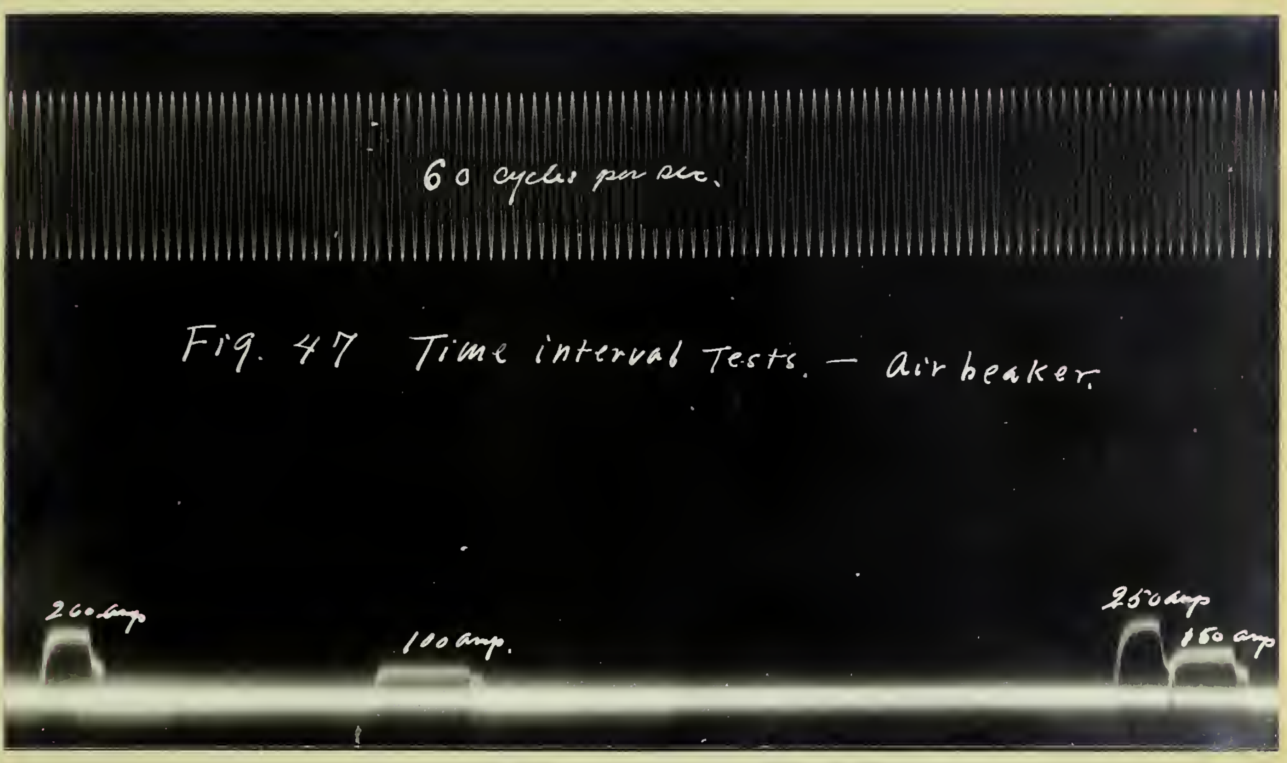


Fig. 47 Time interval Tests. — air beaker.

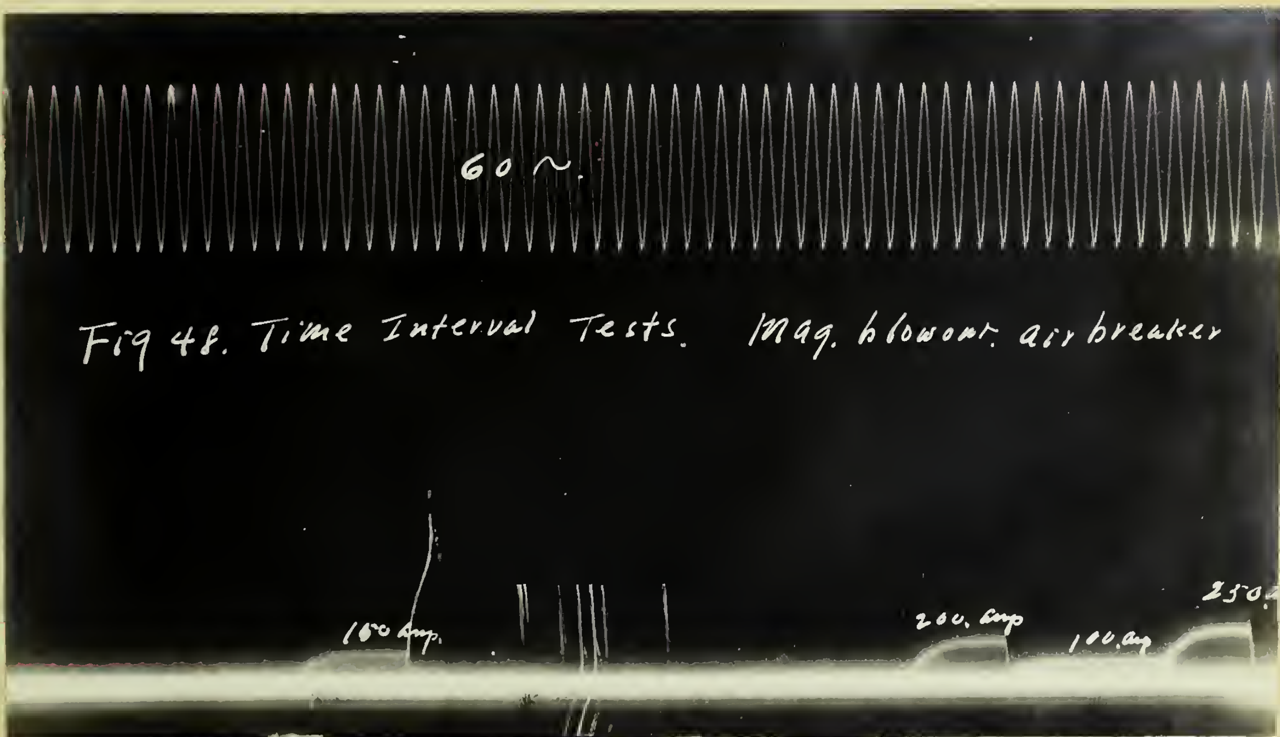


Fig 48. Time Interval Tests. Mag. blowout. air breaker

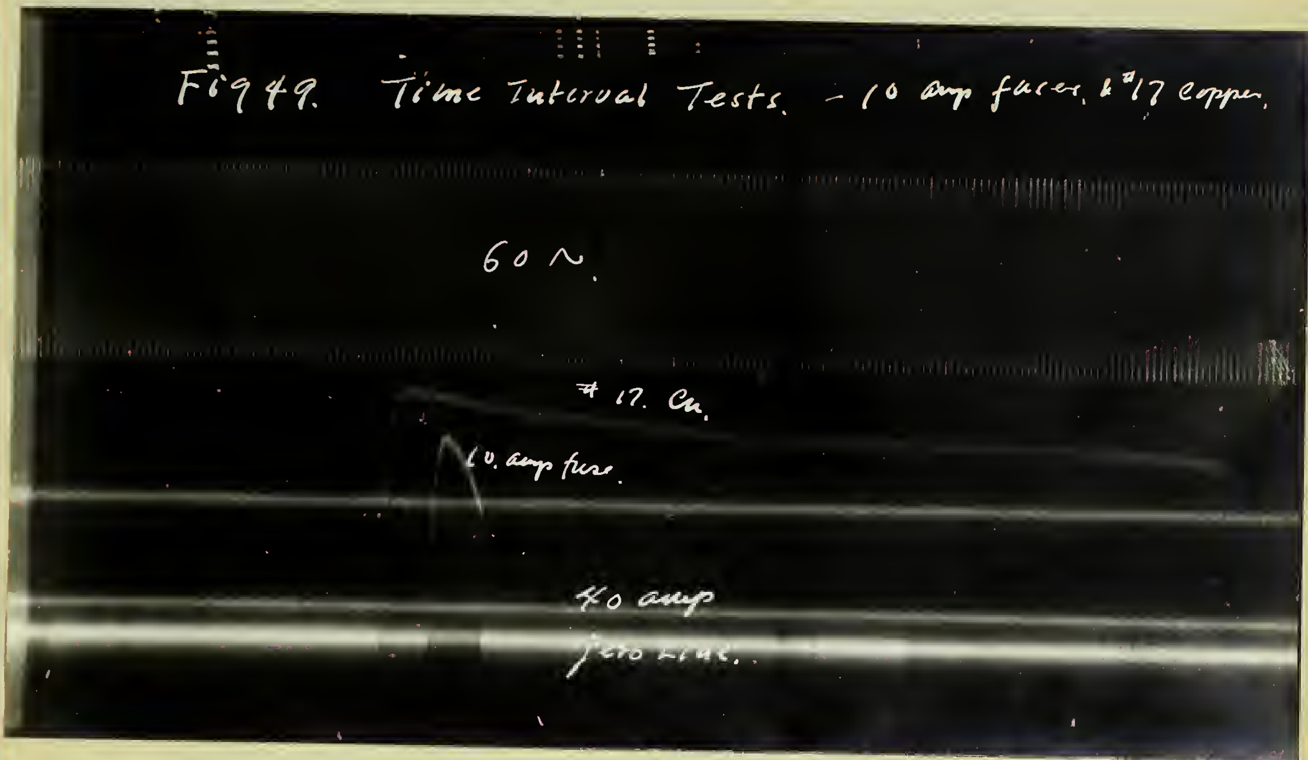


Fig 49. Time Interval Tests. - 10 amp fuses, & #17 copper.

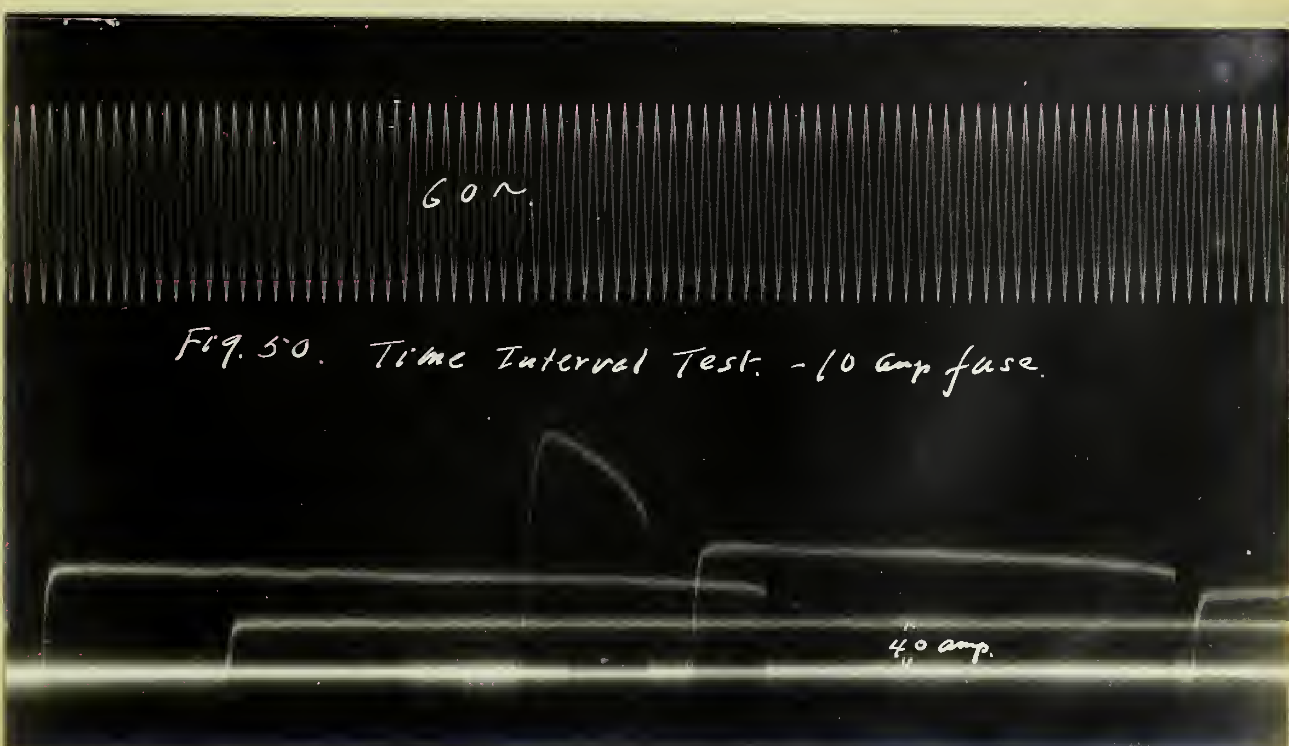


Fig. 50. Time Interval Test. - 10 amp fuse.

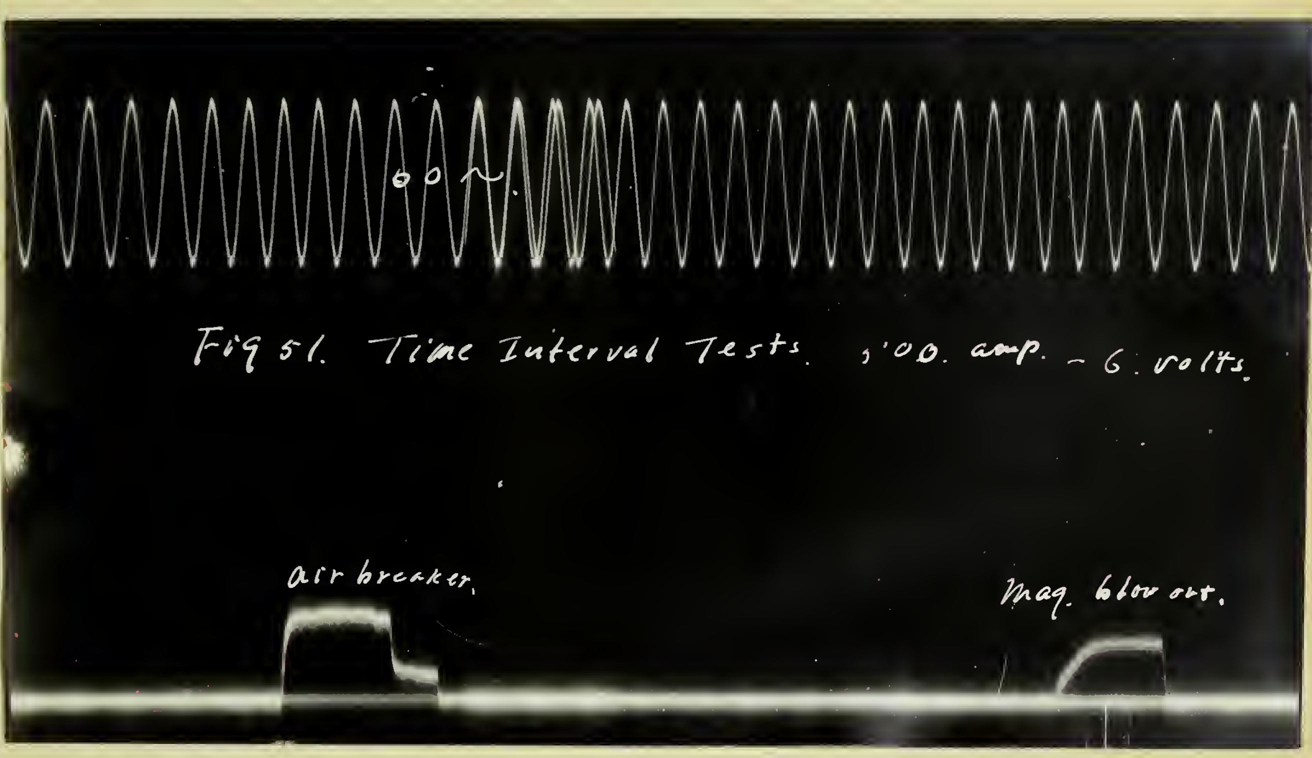


Fig 51. Time Interval Tests. 500. amp. – 6. volts.

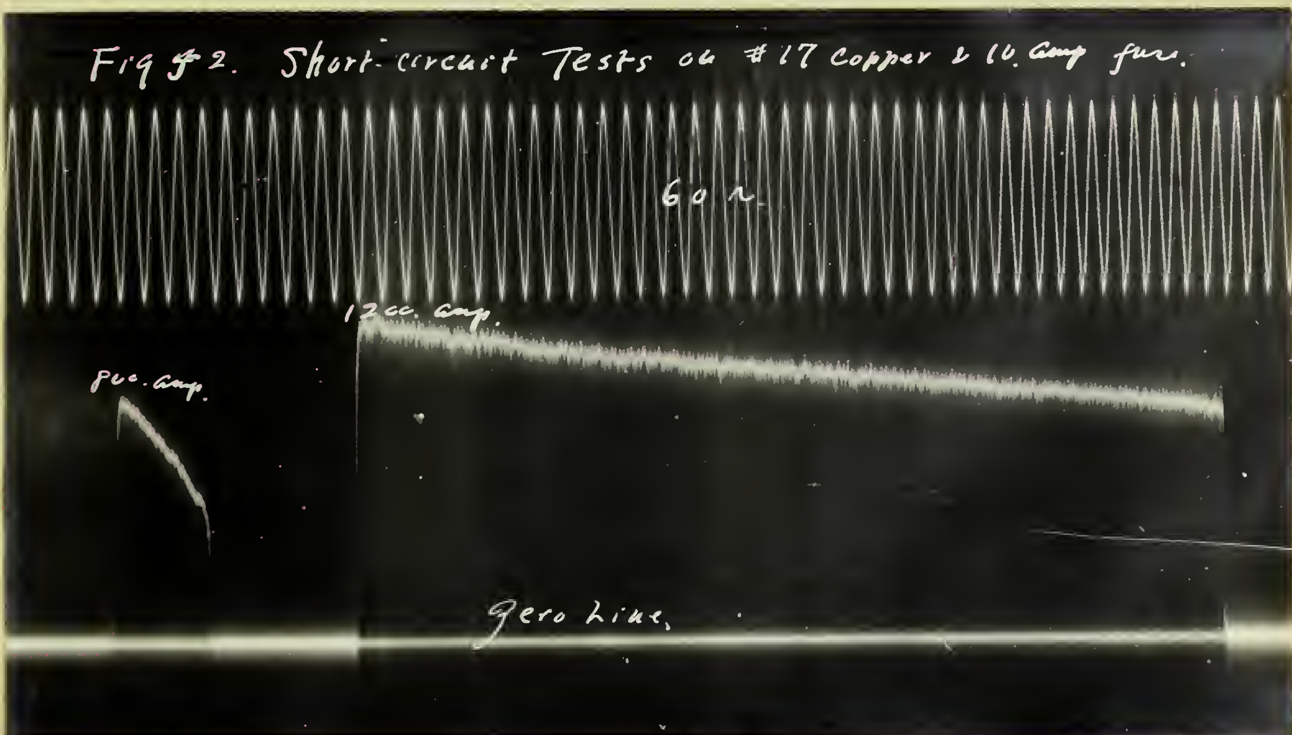
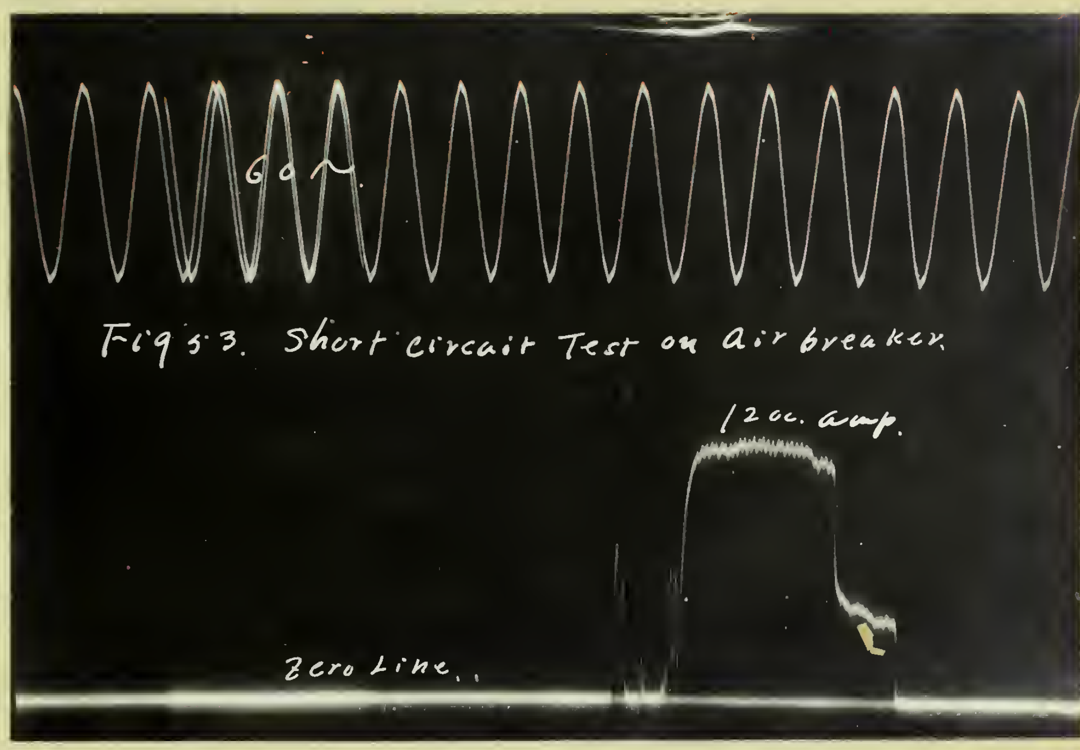
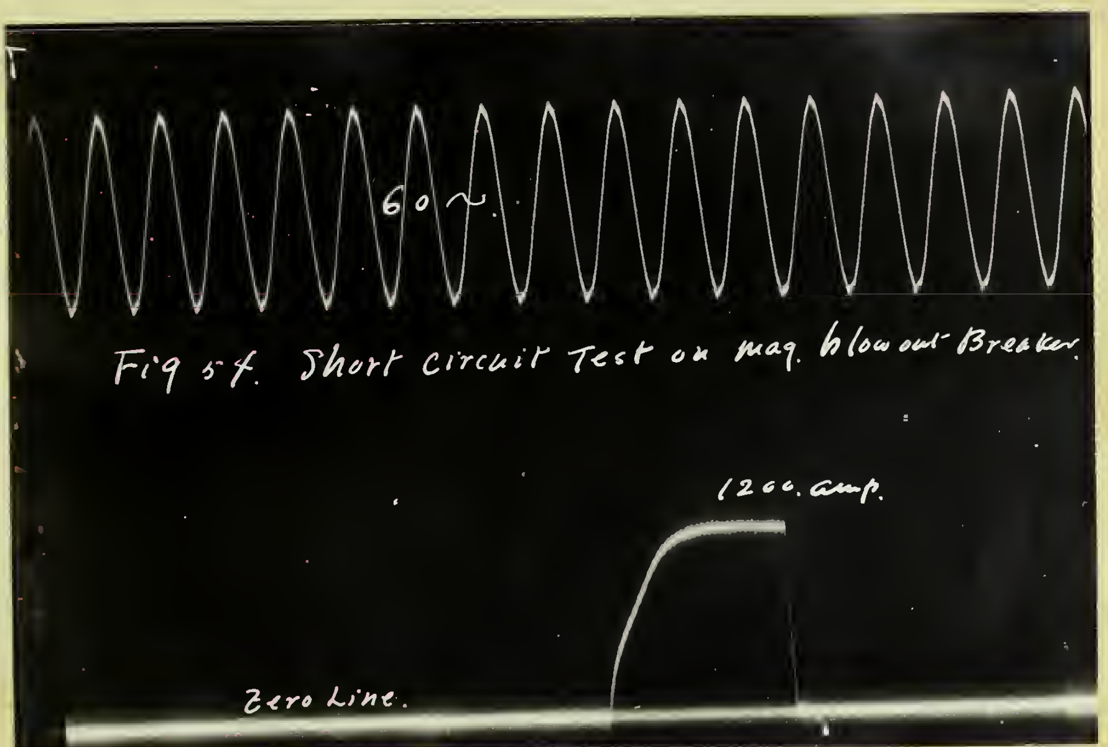


Fig 52. Short-circuit Tests on #17 copper & 10. amp fuse.


60 ~
Fig 53. Short circuit Test on air breaker.
1200. amp.
Zero Line.


60 ~
Fig 54. Short circuit Test on mag. blow out Breaker.
1200. amp.
Zero Line.

Per Cent Overload	Time Intervals in Seconds Average of 3 Fuses
0	permanent
100	28
300	5.5
400	1.9
800	1.2
1,000	.71
3,000	.25
4,400	.13
7,800	.07

Per Cent Overload	Time Intervals in Seconds No. 17 Copper Wire
0	permanent
100	35.0
300	7.0
500	2.5
1,000	1.1
3,000	.67

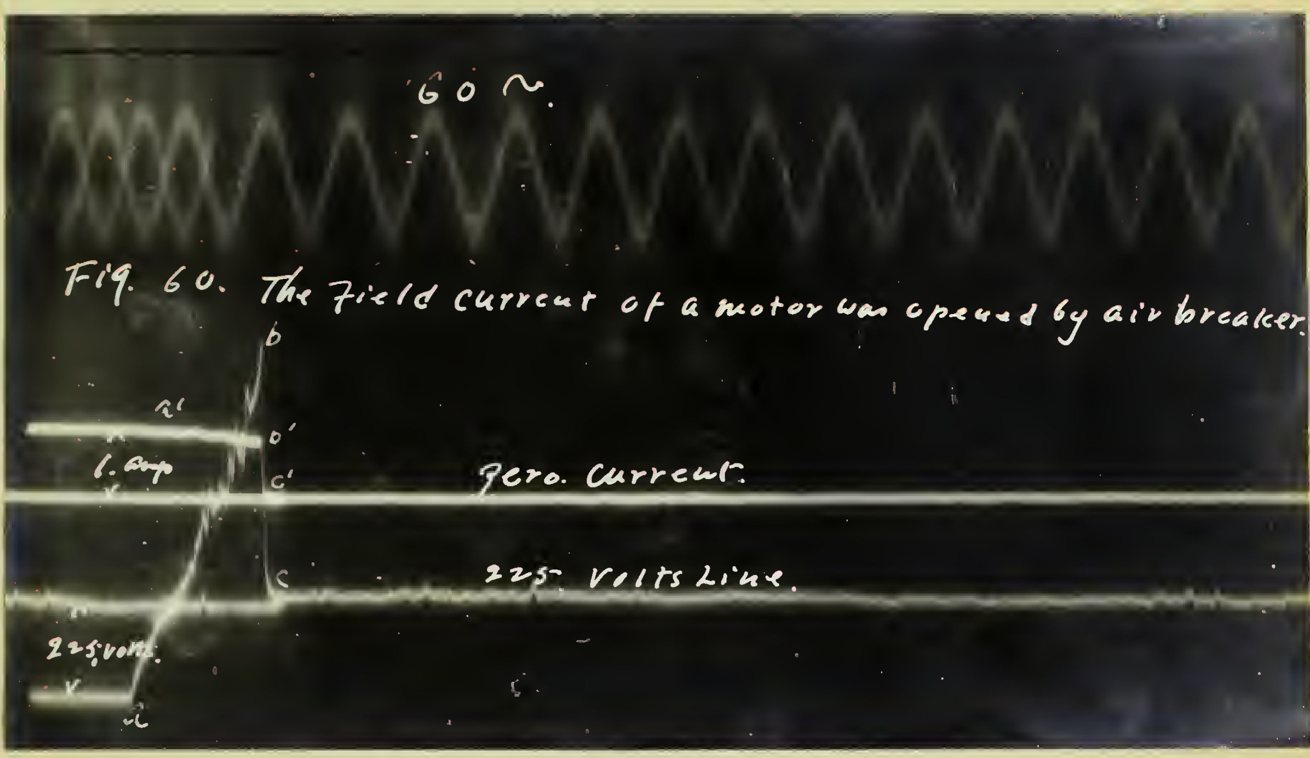
Experiments with an Aluminum Cell.

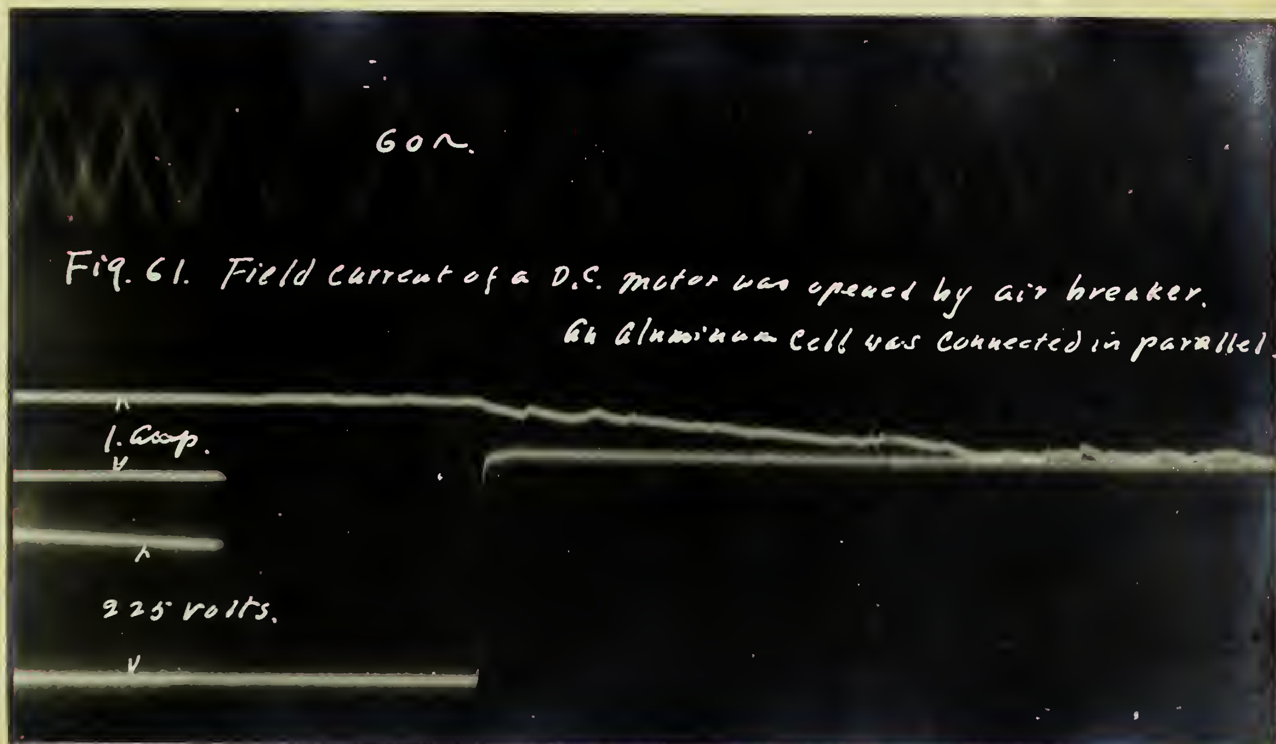
The test was made with the field current of a direct current motor. The voltage impressed was 225 volts, and the current was one ampere. Fig. 60 and Fig. 61 show oscillograms taken in the circuit without the cell, and with it respectively.

In Fig. 60 the instantaneous voltage went up five times the normal value, when the circuit was opened by the air breaker. The current decreased gradually until the arc was extinguished, and then suddenly dropped to zero. There was a large arc between the contact, when it was opened.

An aluminum cell "A", which was used in a lightning arrester was connected in parallel with the circuit breaker. The breaker was tripped, but there was no arc. At the instant the energy was stored in the cell, but it was discharged through the liquid directly when the voltage reached the critical point, say 360 volts in this cell. The current and the voltage were taken in the oscillograms in Fig. 61. The voltage reached the critical point of the cell and stayed in that value until thecell broke down. It took about one second before the current was discharged through the liquid. If an aluminum cell was so made that large amounts of current could be charged and discharged in a fraction of a second, as in case of an ordinary condenser, it will be very useful in connection with circuit breakers. In an ordinary condenser, it stores the energy, but discharges again through the same circuit, when the circuit breaker is completely opened. In the aluminum cell, the energy is absorbed in the cell, and it is not returned to the circuit.

This was tried in a circuit of 100 amperes and 225 volts, but without success, due to the large current and less rise of the voltage. The plate used was two inches square.


60 ~.
Fig. 60. The Field current of a motor was opened by air breaker.
b
1. Amp
c'
Zero. current.
c
225 volts Line.
225 volts.


60 ~.
Fig. 61. Field current of a D.C. motor was opened by air breaker.
An Aluminum Cell was connected in parallel.
1. Amp.
225 volts.

IV. CONCLUSION

1. A decaying current in the actual case, does not follow the theoretical equation,

$$i = \frac{E}{r}$$

on account of variable resistance of the arc.

2. When a circuit is broken by means of separation of contacts by a uniform acceleration, the resistance of arc is very low at start, but it suddenly increases at the last moment. The resistance may be represented approximately by the following equation,

$$r = \frac{K}{I - a\,t^{n}}$$

where K, I, a, and n are constants.

3. The voltage across a circuit breaker, rises four or five times above the normal, when very low voltage circuit is broken, for there is practically no arc. All the stored energy is transformed into the dielectric energy,

$$E = \sqrt{\frac{L}{C}}\, I$$

4. In a circuit whose voltage is higher than 200 volts, the voltage does not rise more than 30 per cent above normal, except in a very highly inductive circuit.

$$E_o = E + e$$

$$\text{Ratio} = \frac{E + e}{E_c}$$

where E_o is the total instantaneous voltage, E is voltage in the circuit and e is the transient voltage. The value of "e" does not depend upon normal circuit voltage, but depends upon the current and the inductance. Hence in a high voltage circuit, the ratio of the transient voltage to the normal voltage is comparatively small.

5. In direct current citcuits the magnetic blow-out breaker, breaks current uniformly, while the oil switch breaks it abruptly at the last moment. Hence the transient voltage is smaller for a magnetic blow-out breaker than for an oil switch, even when the time interval is the same in both cases.

6. In an alternating current circuit, the magnetic field extinguishes the arc at normal zero point, as an oil breaker does. This is due to the residual magnetism at zero point of current.

7. Fuses follow the principle of "the inverse time element" and they are always reliable. They never can fail to blow out in case of short circuit, while circuit breakers may fail to open the circuit, on account of mechanical troubles. Hence it is desirable to connect some fuses in series with other circuit breakers for safety.

8. An aluminum cell, which absorbs a large amount of current during a short time in charging, and discharges it through the dielectric liquid, after the voltage reaches its critical point, is very useful. If it is connected in parallel with an air breaker, the stored energy is dissipated in

the liquid instead of the arc.

9. It is the usual practice to use air breakers in direct current circuits, and oil switches in alternating current circuits, but they may be exchanged to suit some particular purposes.

In textile factories, printing establishments or any other places, where the materials handled may be readily injurious by oil, an air breaker may be employed on alternating current circuit, instead of oil switch.

In mines or in cotton factories, where an arc is very dangerous, an oil switch may be used on direct current circuits, instead of an air breaker. Use of an oil switch on direct current circuit is undesirable when power is greater than 50 K.W.

Successful operation of an oil switch depends upon the condition of the oil, of the contact surfaces and of tripping mechanism, which are enclosed in a box. Hence it needs constant care by attendants. Insufficient oil or carbonization of oil may turn the oil to fuel, and may result in destruction of the breaker. To avoid these disadvantages and to save the first cost, an air breaker may be used instead of an oil switch, in alternating current circuits, if arc is not so un-desirable. An arc may be extinguished in a small fraction of a second, in high tension lines, if the magnetic field is set up strong enough.

Rise of transient voltage is even less than that of an oil switch, for the arc is not extinguished abruptly as in case of an oil switch.

10. In highly inductive circuits, it is hard to extinguish the arc at the first zero point, for the voltage is great enough to puncture the insulation at the first zero point.

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